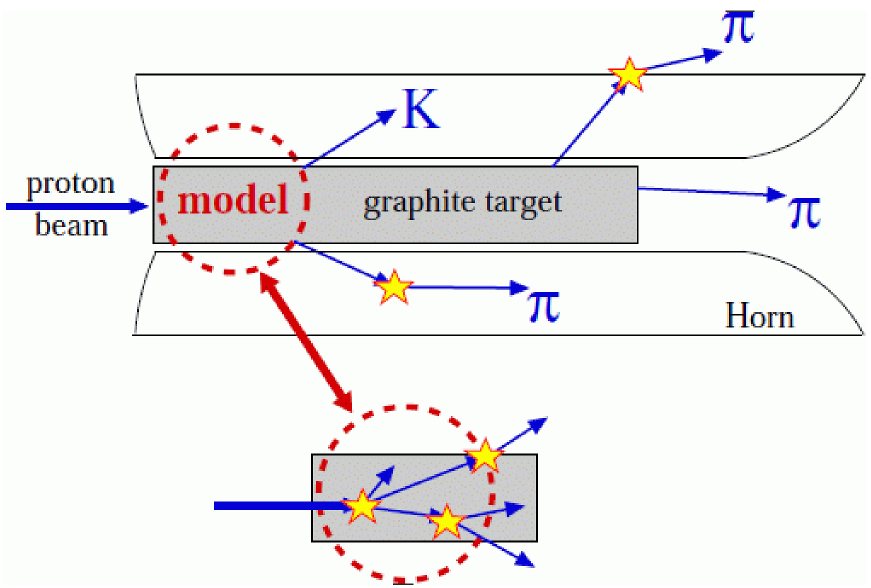
Hadron production experiments to constrain the neutrino beam

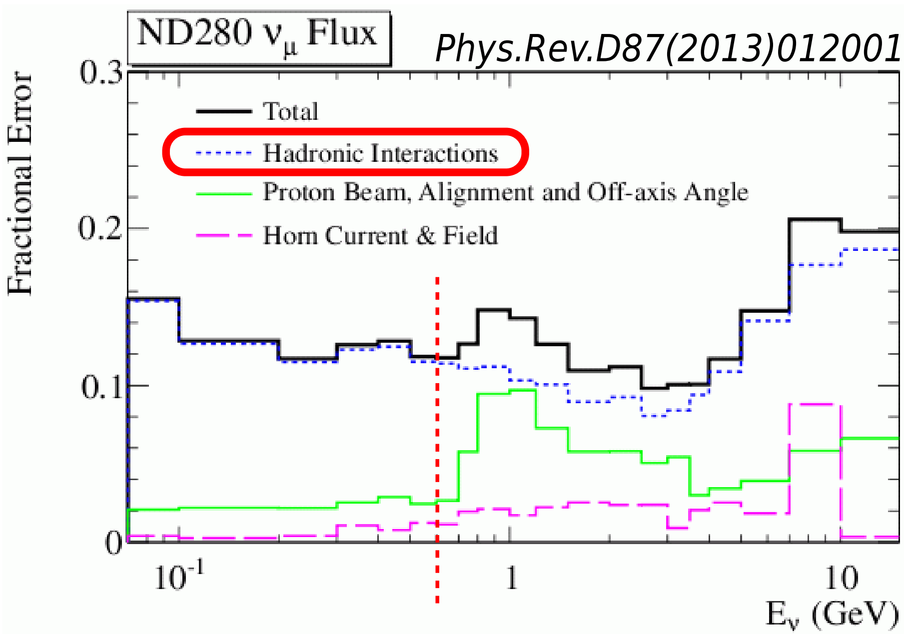
Alexander Korzenev,
University of Geneva

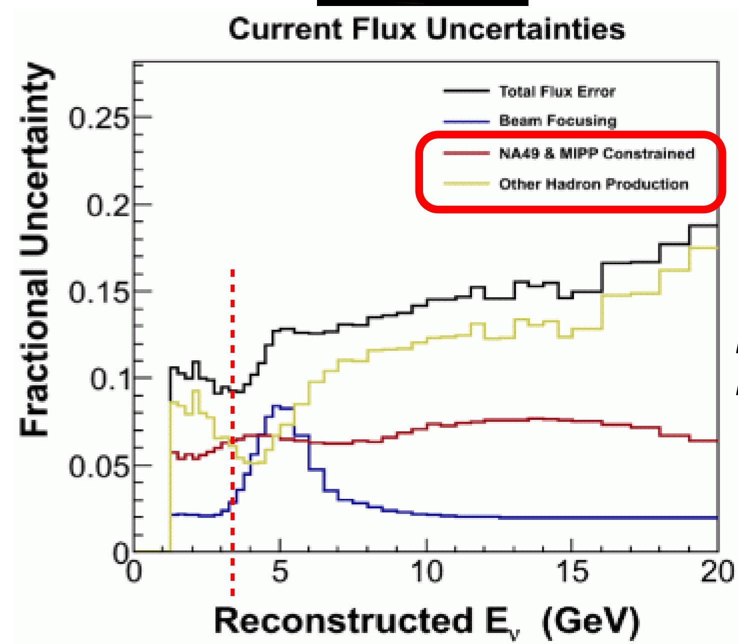
Neutrino 2014
Boston USA, June 6



- Why hadron production measurements?
- Approaches for the ν flux constraint:
  - Re-weighting at the interaction vertex
  - The actual target measurements

Motivation for an ancillary hadron production experiment





D.Harris NuInt14

- Uncertainty on the neutrino flux is a dominant contribution to systematics of measurements: 10 – 20 %
- Uncertainty on hadronic interactions is dominant contribution to the flux uncertainty

Few examples

Hadron production experiments

neutrino experiments

HARP, CERN-PS214
1.5-15 GeV beam

(Mini-, Sci-, Micro-)BooNE at Fermilab
K2K (KEK to Super-Kamiokande)

NA20 & SPY/NA56, SPS
400-450 GeV beam

WANF (NOMAD, CHORUS)
CNGS (OPERA, ICARUS)

NA49, CERN-SPS
160 GeV beam

MIPP, FNAL-E907
120 GeV beam

NuMI beamline in Fermilab
(MINOS, MINERvA, NOvA)

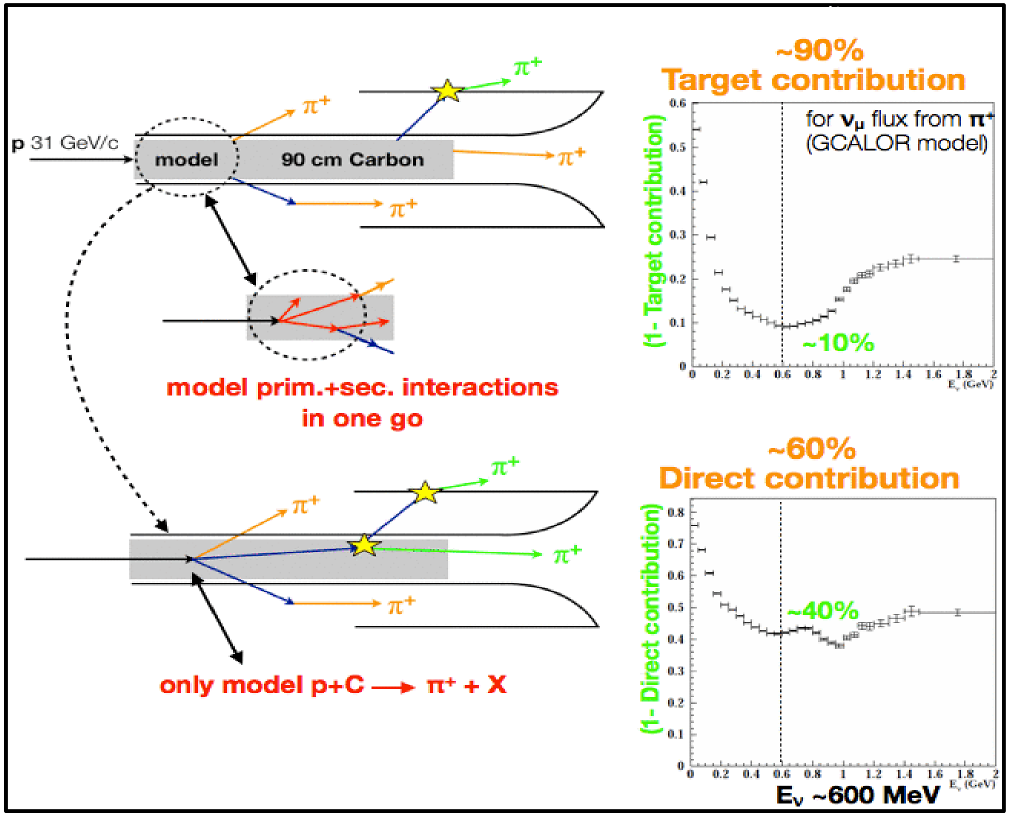
NA61/SHINE CERN-SPS
13-400 GeV beam

T2K (JPARC to Super-Kamiokande)
NuMI (MINOS+,MINERvA, NOvA)
LBNE, LBNO, T2HK

Normally results of several hadron production experiments are used

Approaches for the ν flux constraint

1) Traditional: re-weighting at the interaction vertex
   - Model dependent: x_F scaling assumed for extrapolation
   - Results of many hadron production experiments are used



2) The actual target measurements
   - Hadron yields on a surface of target
   - Never used so far
   - HARP, NA61, MIPP

3) Additional constraints come from
   - Muon monitor measurements
   - In situ techniques (direct measurement of the ν flux)
   - ...

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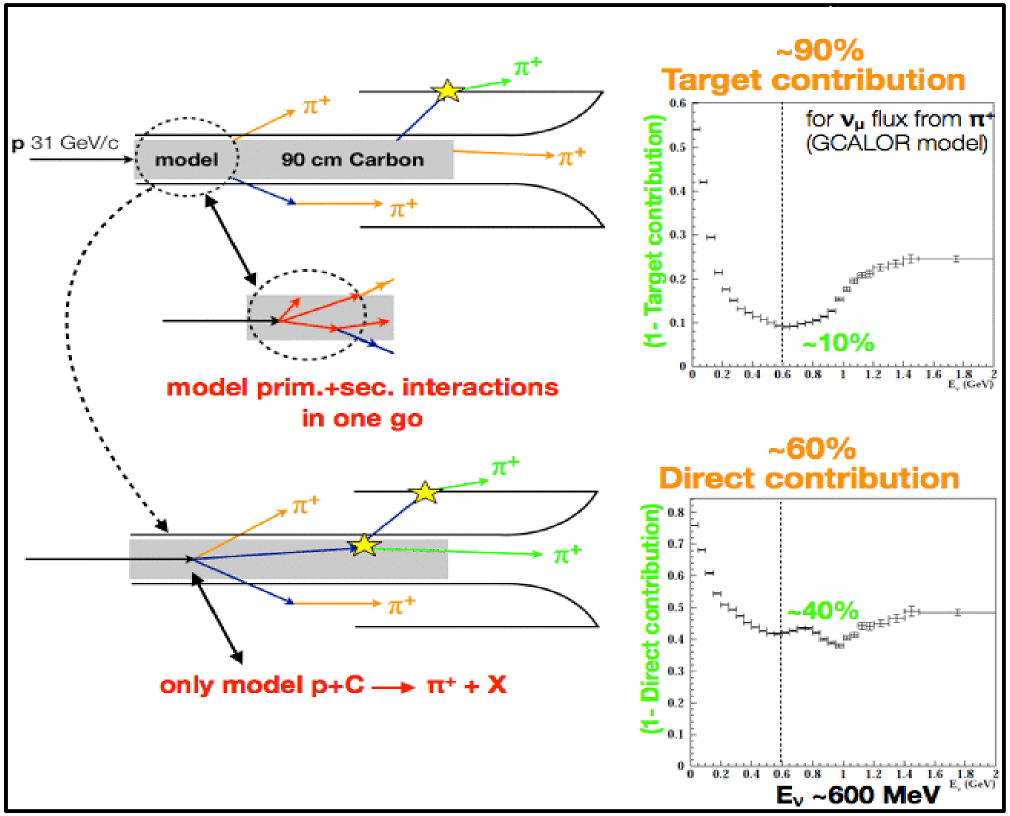

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MINERvA's posters:
- Low-nu flux technique, L.Ren
- Flux constrain by νe scat., J.Park

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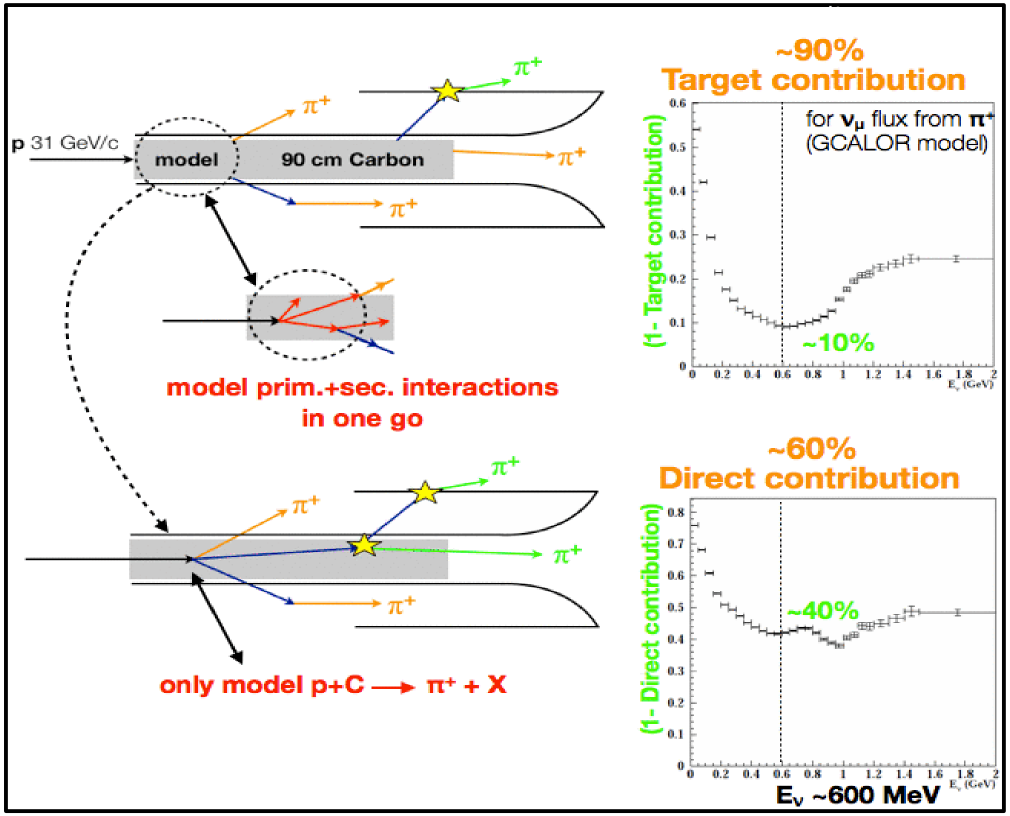

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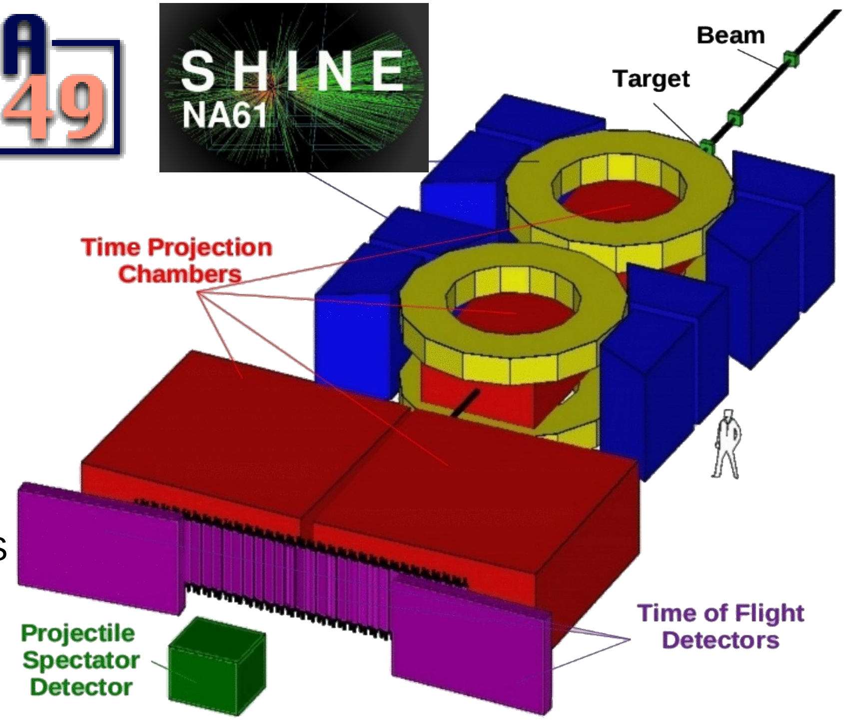
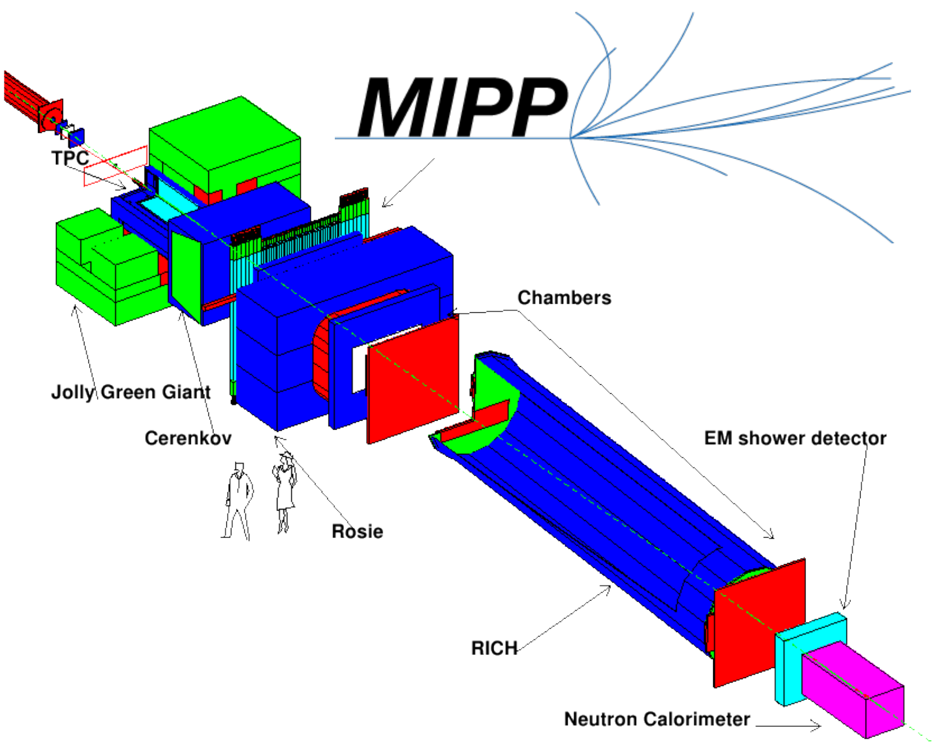
One can feel safe if all methods give consistent results !

Data for beamline of T2K

- **NA61/SHINE** approved in 2007
- Successor of NA49, H2 beamline of CERN SPS
- Pilot run with pC data at 31 GeV in 2007. Main dataset in 2009 and 2010
- New results (run 2009) on $\pi^{\pm}$, $K^{\pm}$, p, Λ, K^0_S
- Thin and replica target measurements





Data for NuMI beamline in Fermilab

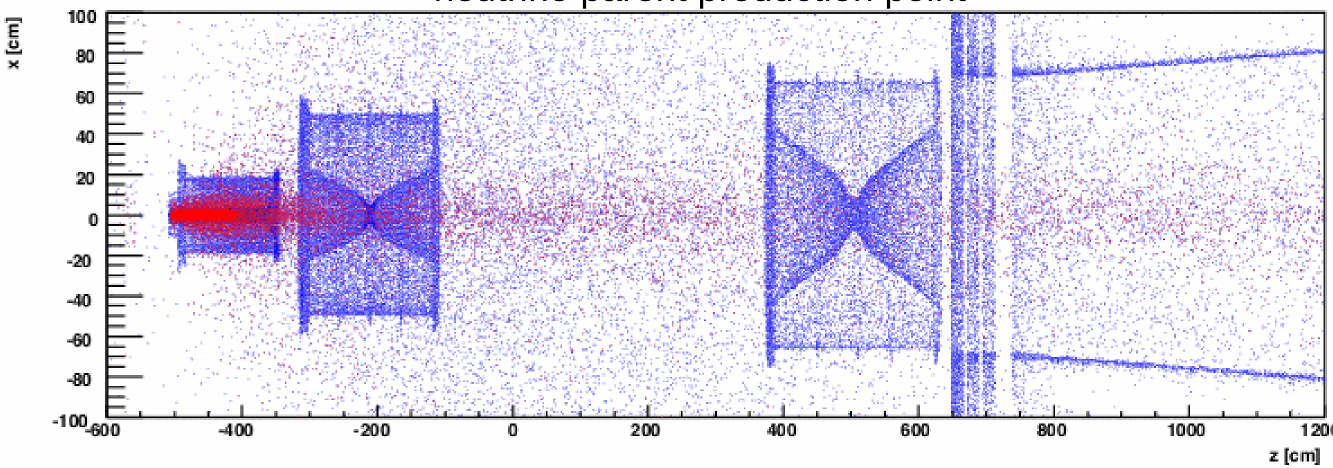
- NA49 data to constrain the ν flux
- **MIPP**: approved in 2001, datataking in 2005 and 2006
  - Ratio of hadron cross sections π^-/π^+, K^-/K^+, π/K released in 2007
  - New results on $\pi^{\pm}$ production yields off NuMI target: arXiv:1404.5882
- Extensive program is foreseen in NA61 (pilot data at 120 GeV in 2012)

Traditional approach: re-weighting at the interaction vertex

- NA61 data for the T2K simulation
- New results of NA61
- NA49 & MIPP data for the NuMI simulation

NA61 data in the T2K experiment

neutrino parent production point



Red: parent produced in target
Blue: parent produced outside the target

Hadronic interaction in the target are modeled with FLUKA, outside the target with GEANT3 (GCALOR)

Main set of hadron production data

Experiment	Beam p[GeV/c]	Target	Particle
NA61/SHINE	31	C	$\pi^{\pm}$, $K^{\pm}$, p
Eichten *et al.*	24	Be, Al, ...	p, $\pi^{\pm}$, K^{+}
Allaby *et al.*	19.2	Be, Al, ...	p, $\pi^{\pm}$, $K^{\pm}$
E910	6.4-17.5	Be	$\pi^{\pm}$

Major part of the T2K phase space (NA61/SHINE)

For forward kaons (Eichten *et al.*)

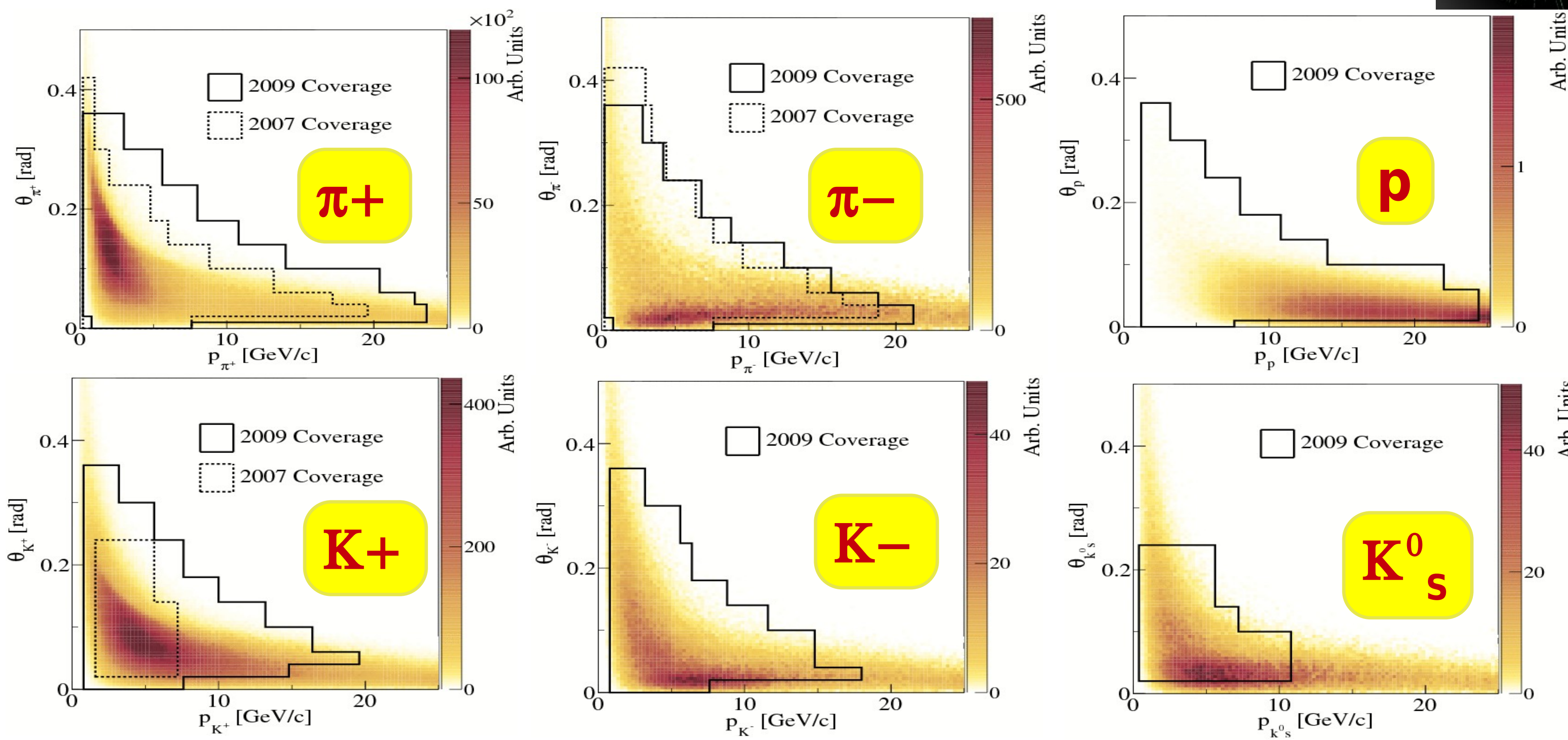
For tertiary pions (E910)

- Interaction chain for hadrons is stored, to be **weighted later with real measurements**
- Tuning of tertiary pions requires extrapolation from NA61 data
  - Extrapolation to different incident nucleon momenta is done assuming Feynman scaling ($x_F=p_L/p_L^{max}$)
  - Extrapolation from carbon to aluminum using

$$E\frac{d^3\sigma(A_1)}{dp^3} = \left[\frac{A_1}{A_0}\right]^{\alpha(x_F,p_T)} E\frac{d^3\sigma(A_0)}{dp^3}$$

(T2K) K.Abe et al., Phys.Rev.D87(2013)012001

Phase space of hadrons contributing to the predicted ν flux at SK (250 kA)



Summary of data collected by **NA61** for T2K

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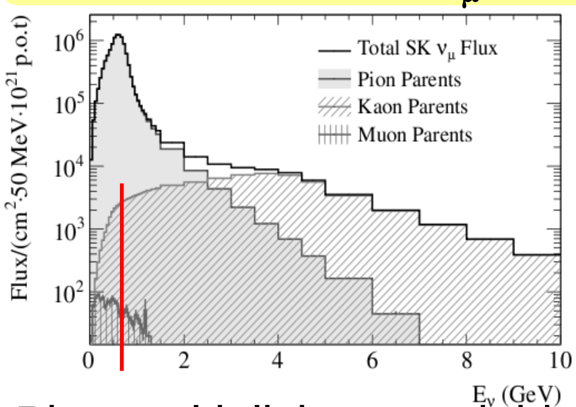
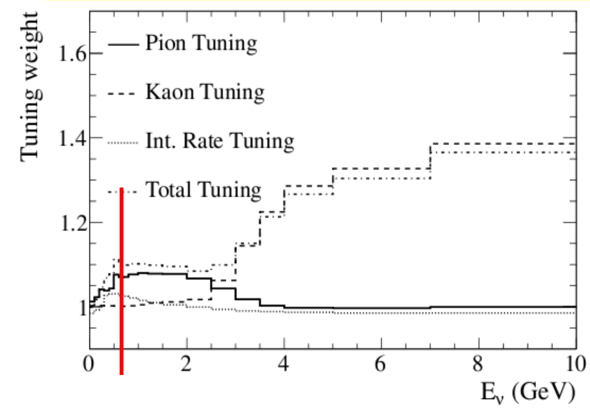
		2009	2.8	to be released in 2014	-
		2010	~10	calibration	-

Tuning of ν_μ flux using NA61 spectra

Decomposition of ν_μ flux



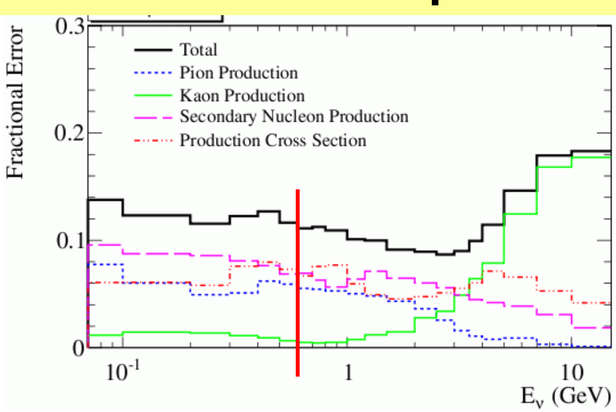
Re-weighting coefficient



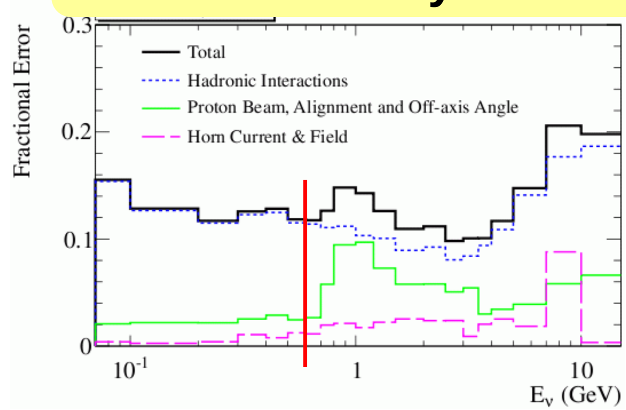
Pilot data of NA61 (2007) have been used

- Pion multiplicity re-weighing has the largest effect at low energies, while the kaon multiplicity re-weighting is important at high energies.

Error due to hadron production



All sources of systematics

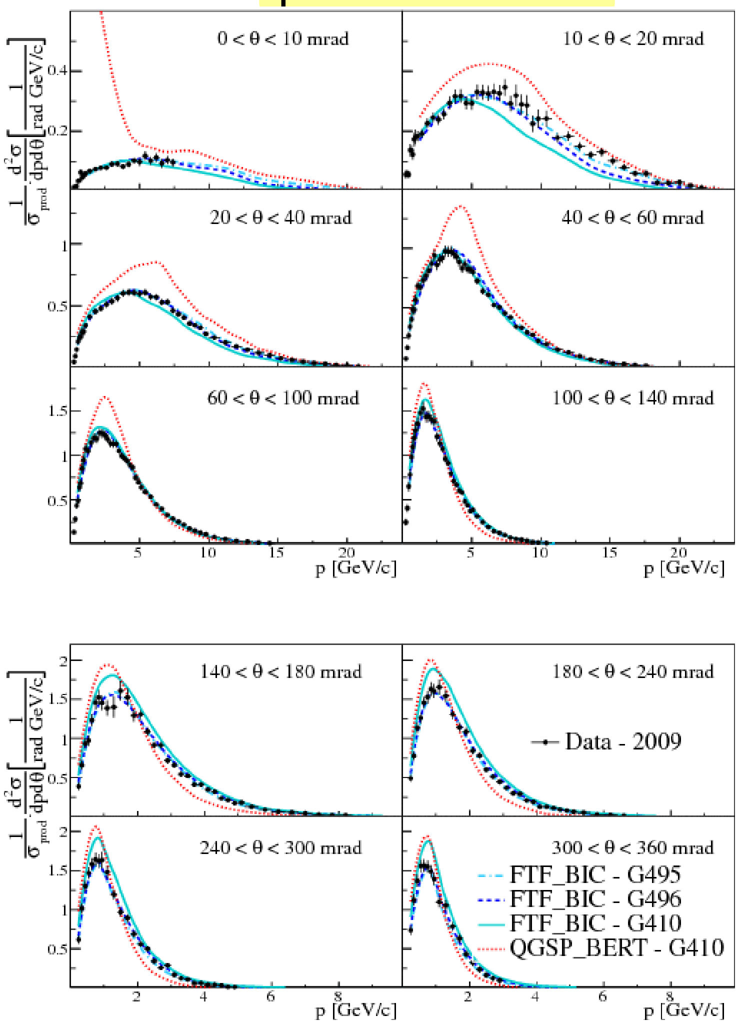


- Total flux uncertainty is dominated by the hadron interaction uncertainties

(T2K) K.Abe et al., Phys.Rev.D87(2013)012001

New NA61 measurements for T2K at 31GeV

$p + C \rightarrow \pi^+ + X$



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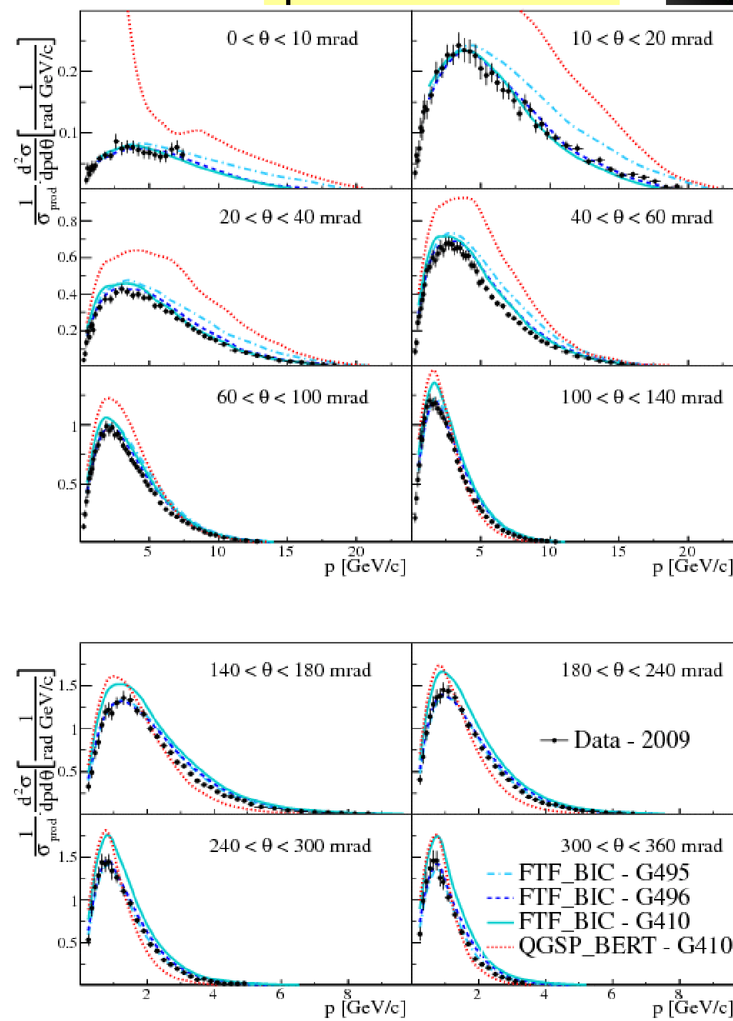

- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- Typical uncertainty for regions which are important for ν flux is ~4%
- Recent versions of FTF_BIC describe data reasonably

New NA61 measurements for T2K at 31GeV

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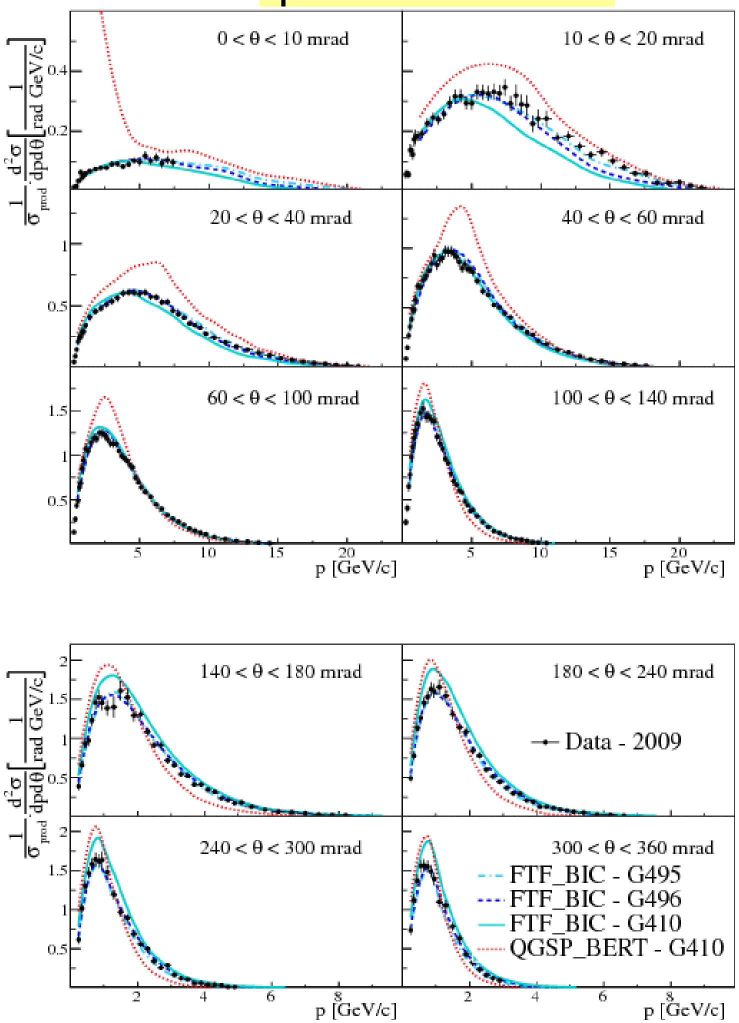
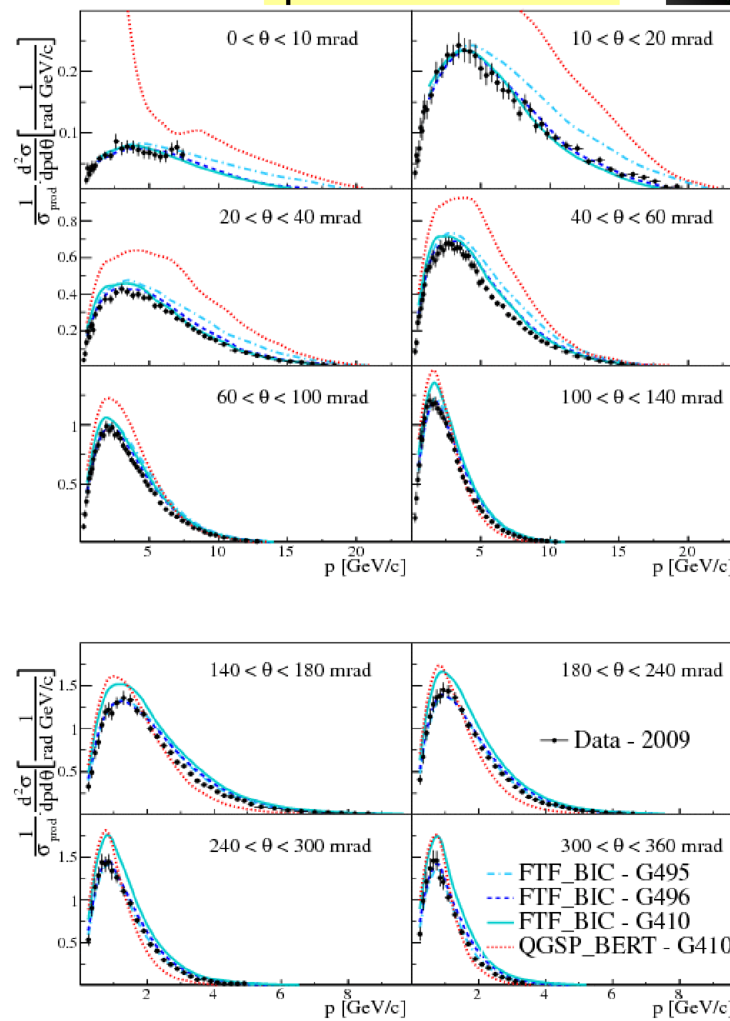


$p + C \rightarrow \pi^{-} + X$



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- Typical uncertainty for regions which are important
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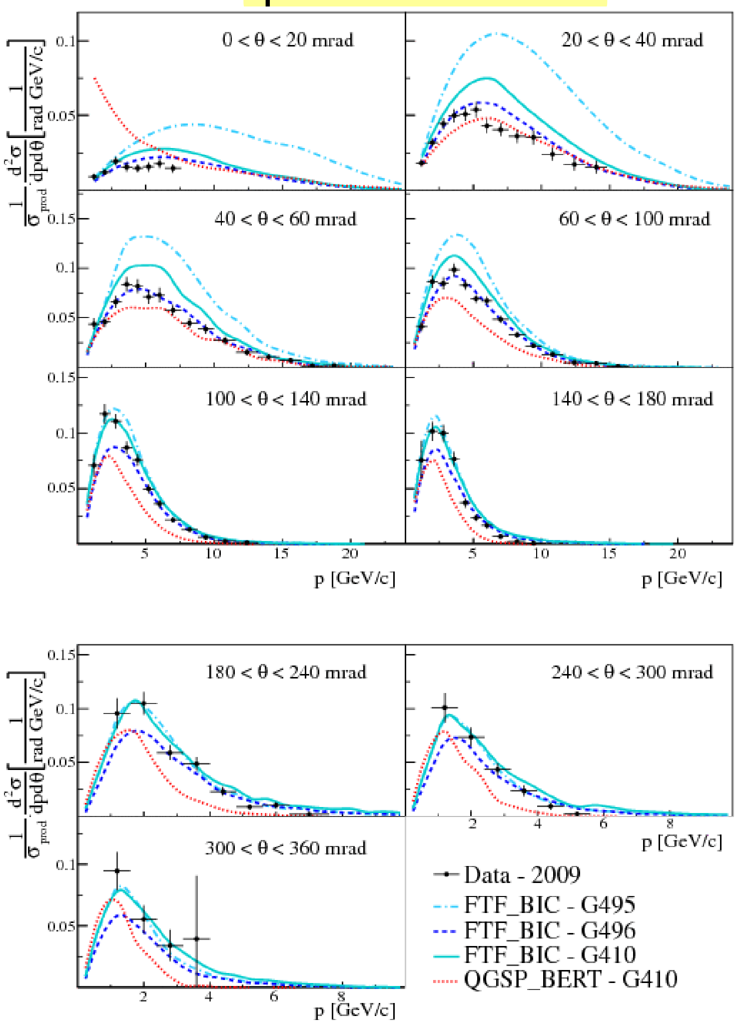
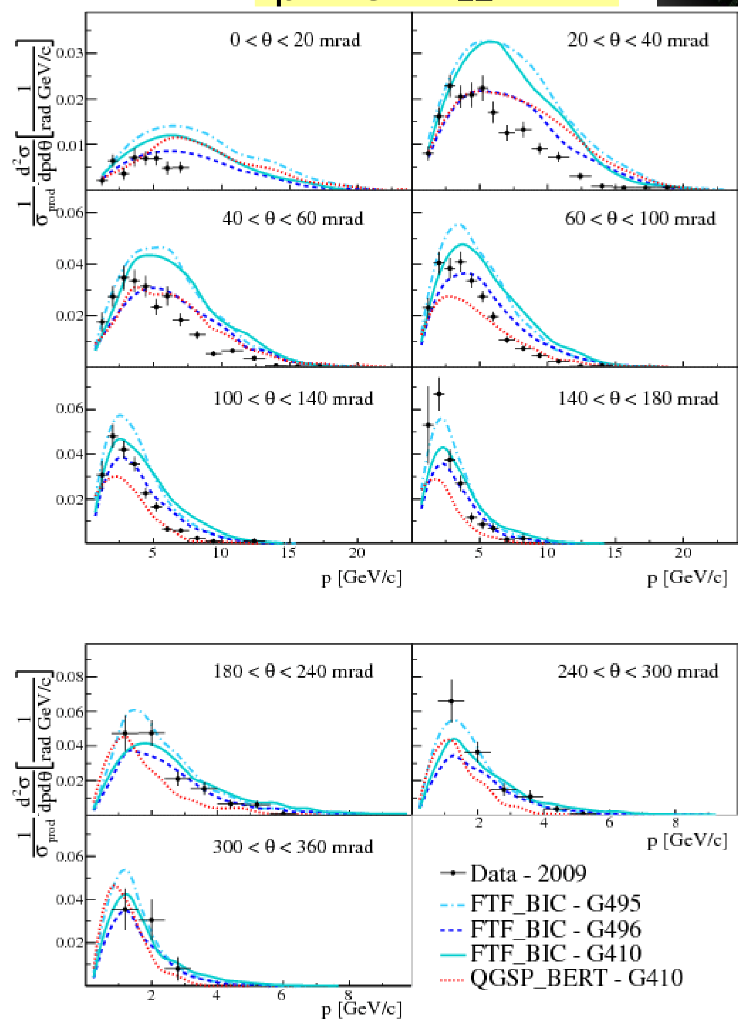
Poster by M.Posiadala:
- $\pi^{\pm}$ multiplicities from p-C interactions at 31 GeV for T2K

New NA61 measurements for T2K at 31GeV

$p + C \rightarrow K^{+} + X$

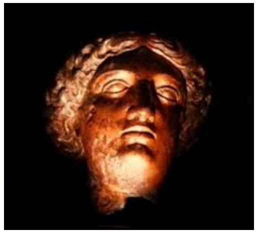


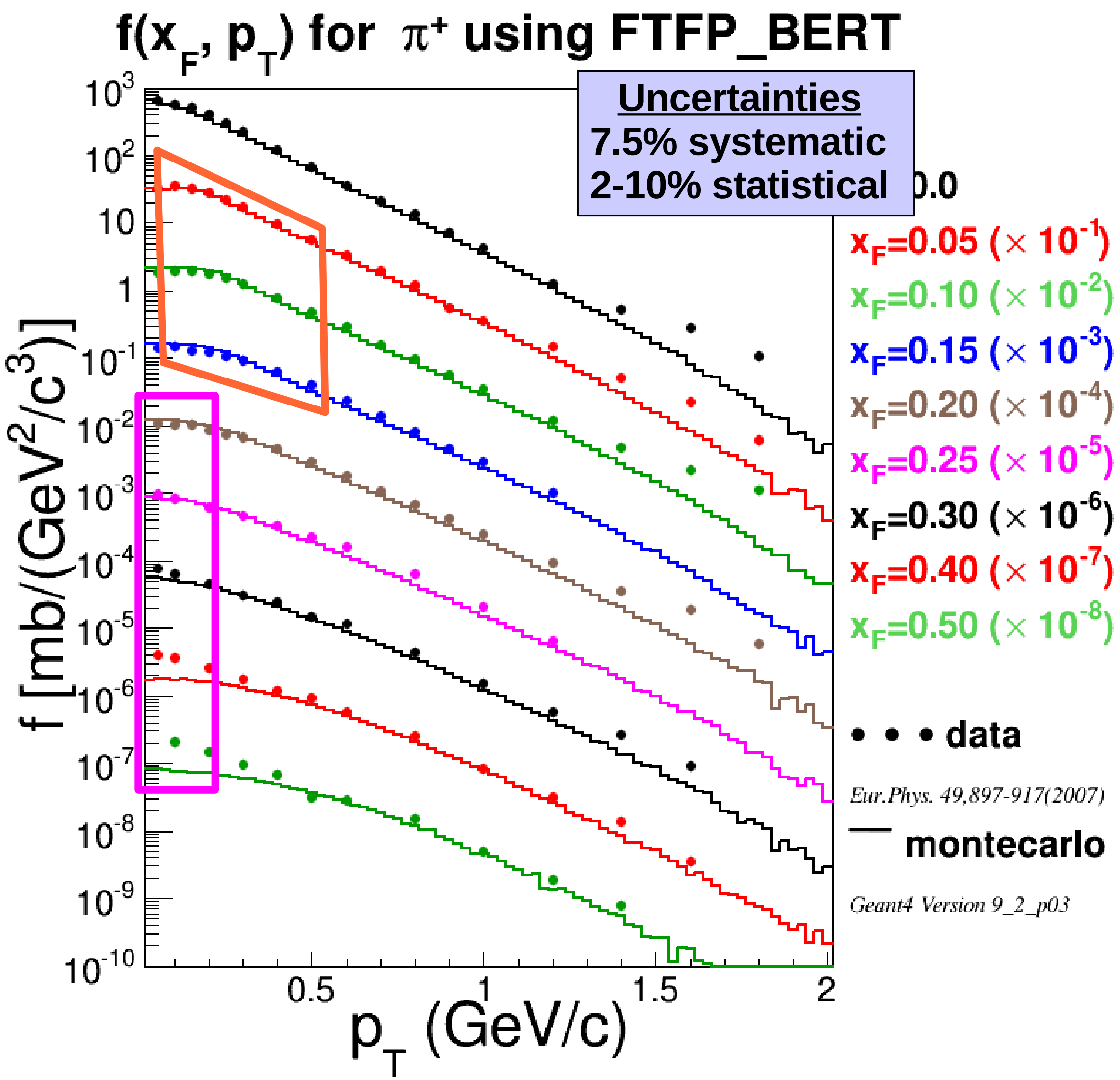
$p + C \rightarrow K^{-} + X$

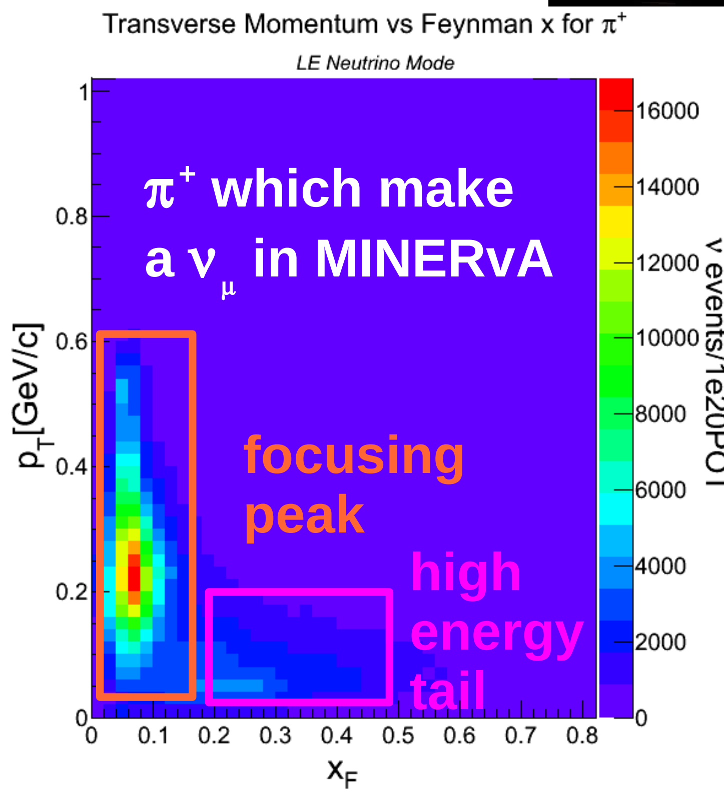


- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- Typical uncertainty in a central region is ~15%
- Recent versions of FTF_BIC describe data reasonably

NA49 data for the NuMI simulation



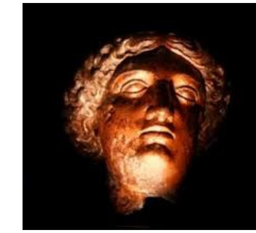


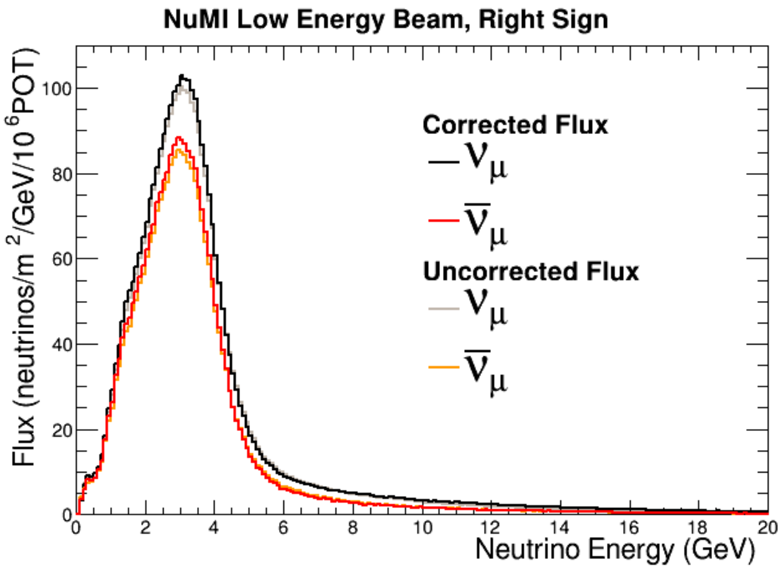


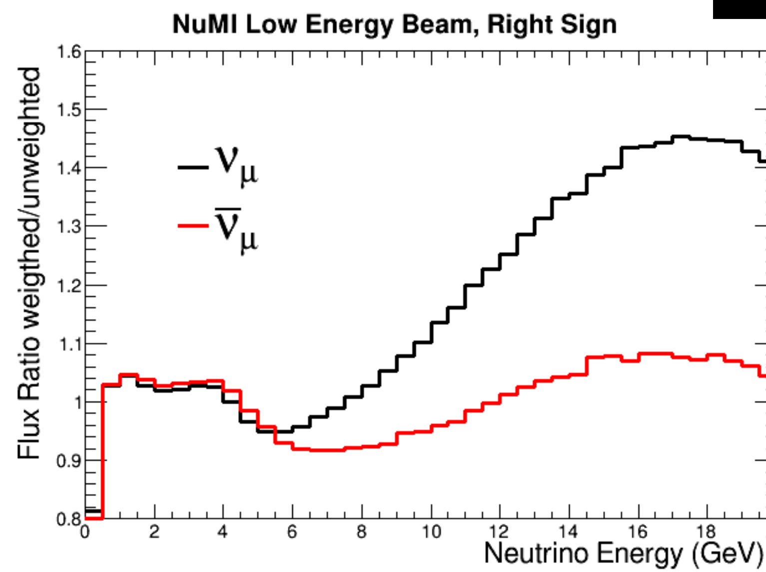
- Cascade leading to ν is tabulated at generation. Save kinematics & material
- In analysis, interactions reweighted as σ(data)/σ(MC)

- NA49 measurements at 158 GeV: p+C → ($\pi^{\pm}$,$K^{\pm}$,p)+X
- MIPP measurements at 120 GeV: ratio of cross sections K/π

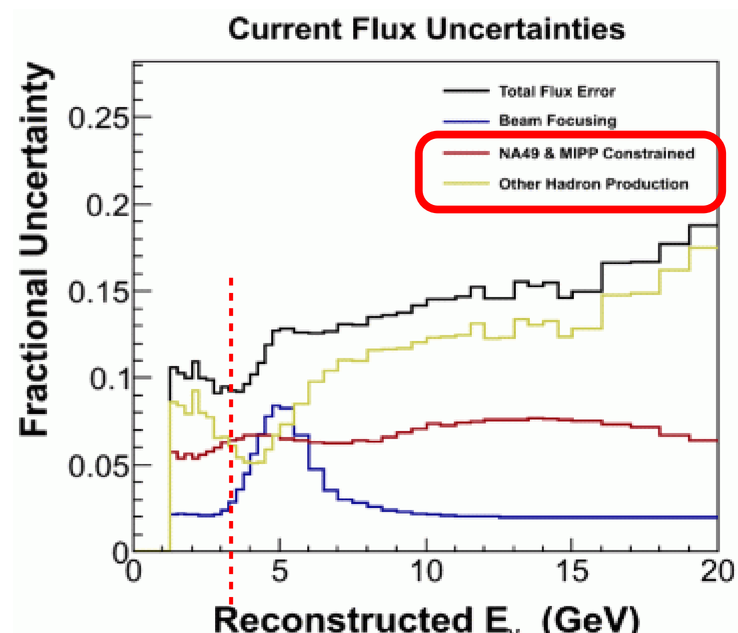
NA49 data for the NuMI simulation







- FLUKA is used to translate NA49 measurements to proton energies between 12 and 120 GeV
- Interactions not constrained by the NA49 data are predicted using FTFP
- Effect of corrections is < 5% at peak energy
- Flux uncertainty is a dominant contribution to the cross section systematics
- Hadron interactions dominates in the systematics of the flux



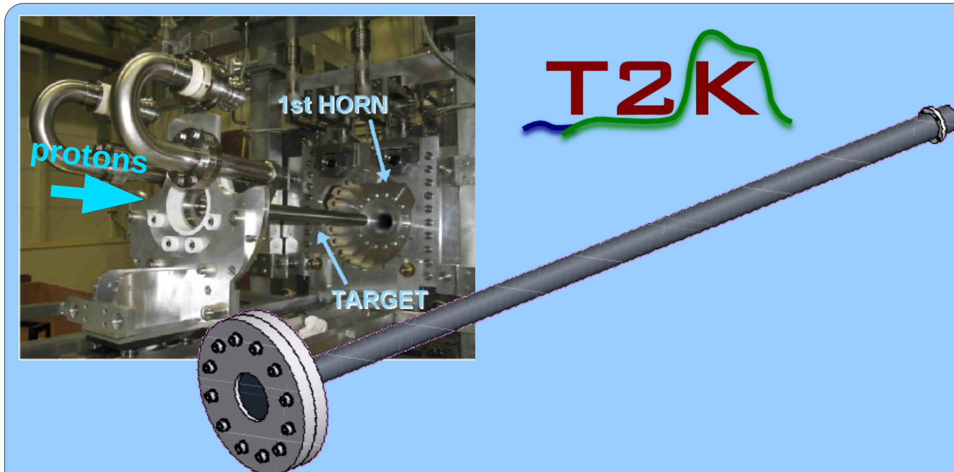
D.Harris, NuInt14, May 23, 2014

The actual target measurements: parametrization of hadron yields outside the target

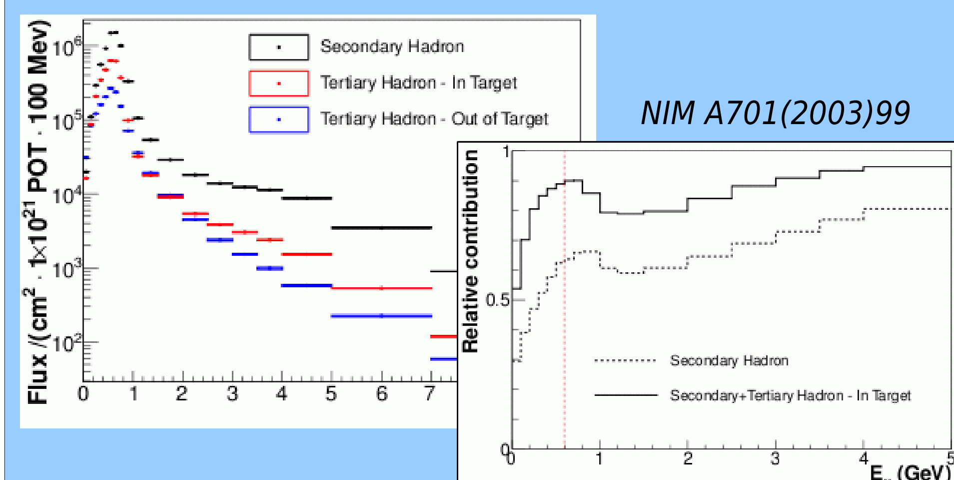
- Results of NA61 for T2K
- New results of MIPP for NuMI

The actual target measurements

Measurement of hadron yields at the target surface (no matter how they are produced)



Graphite rod 90 cm long and Ø = 2.6 cm. Replica target was delivered to CERN to be used in NA61

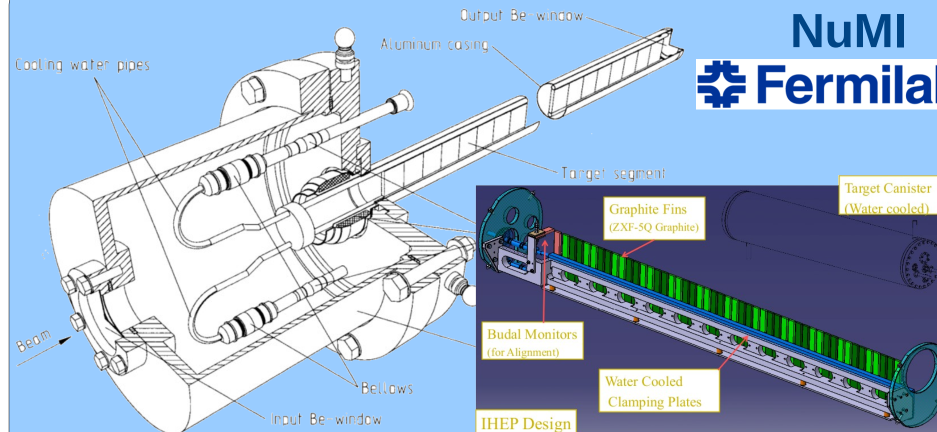


NIM A701(2003)99

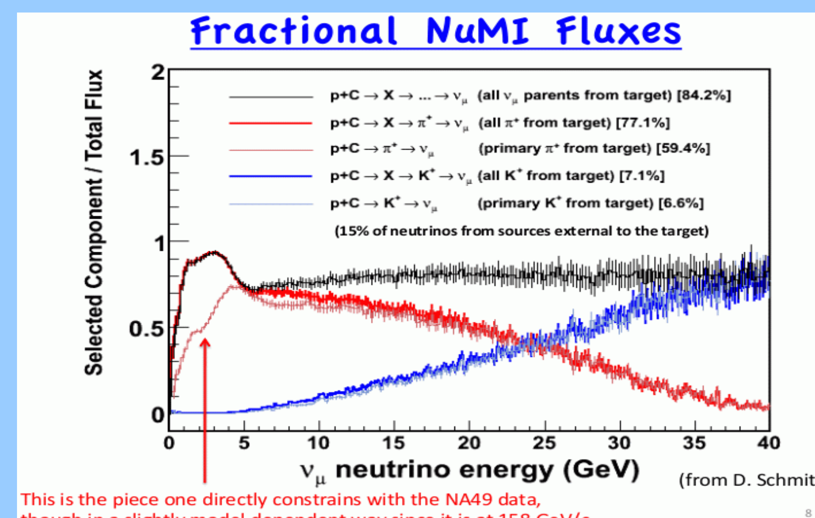
Ancillary experiment: NA61/SHINE in CERN

NuMI

Fermilab



Canister 90 cm long and Ø = 3 cm. 47 graphite segments soldered to water cooling line



Ancillary experiment: MIPP in Fermilab

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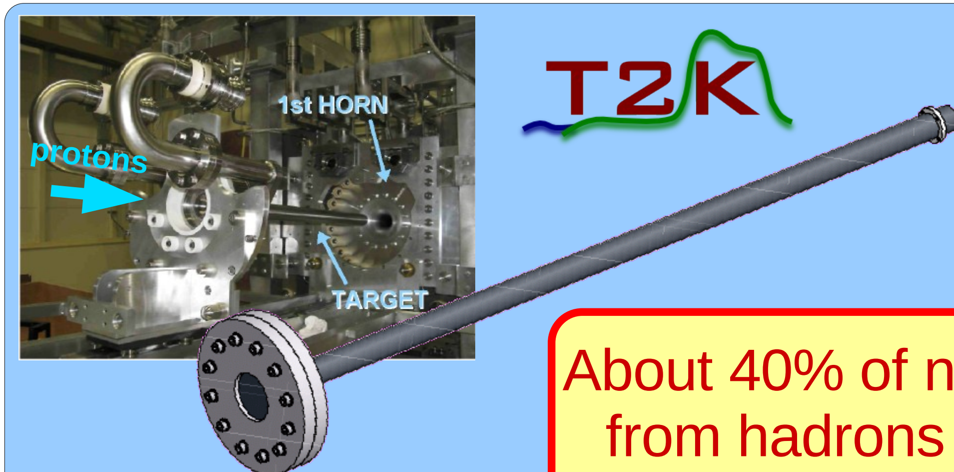

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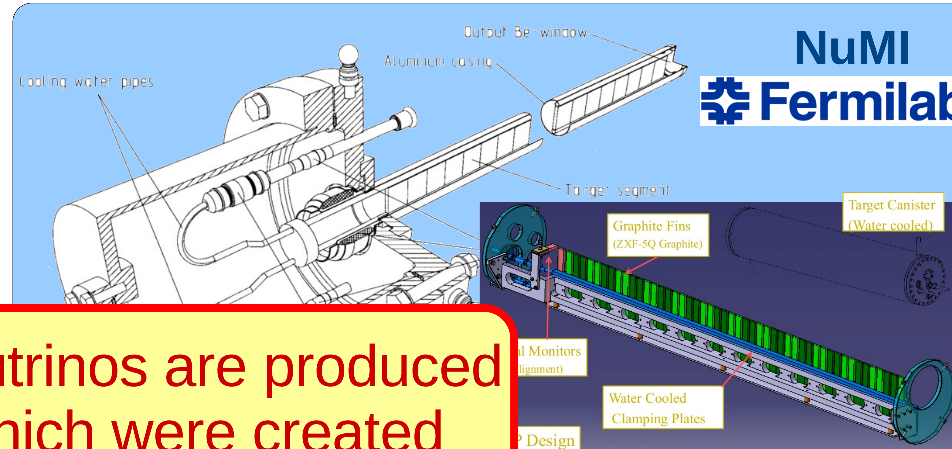

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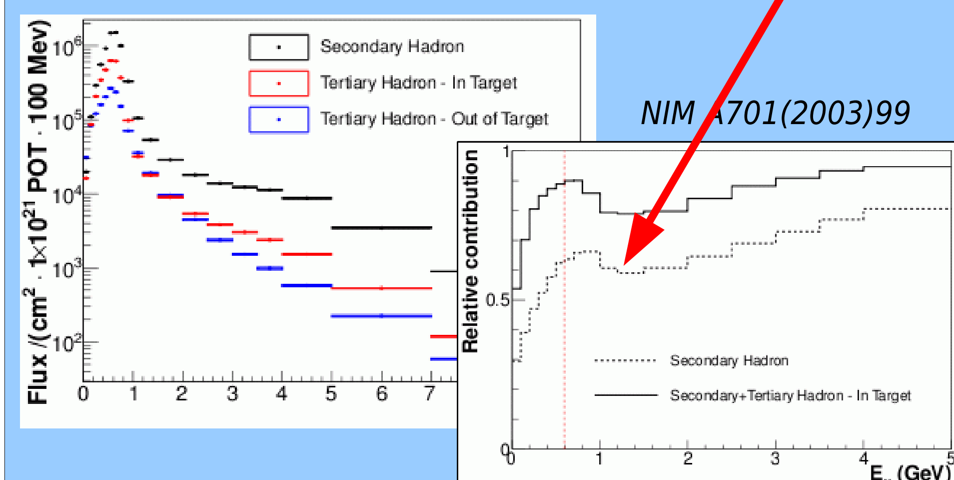
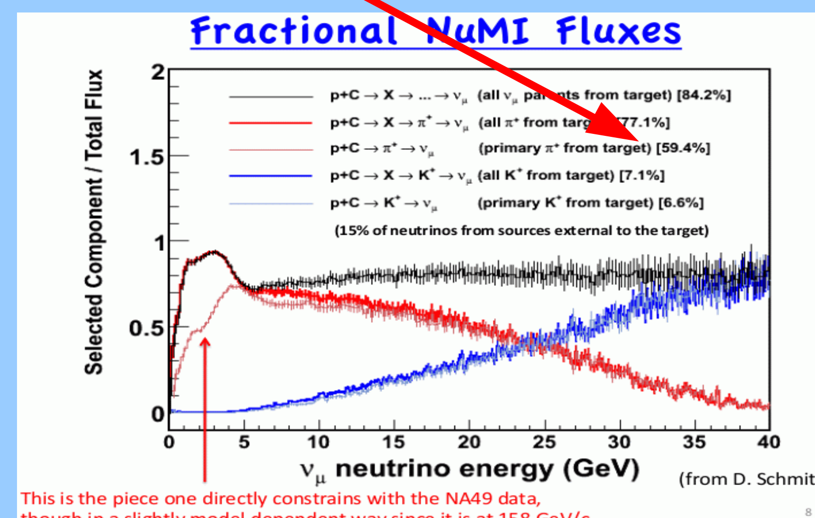
About 40% of neutrinos are produced from hadrons which were created in secondary interactions





Ancillary experiment: NA61/SHINE in CERN

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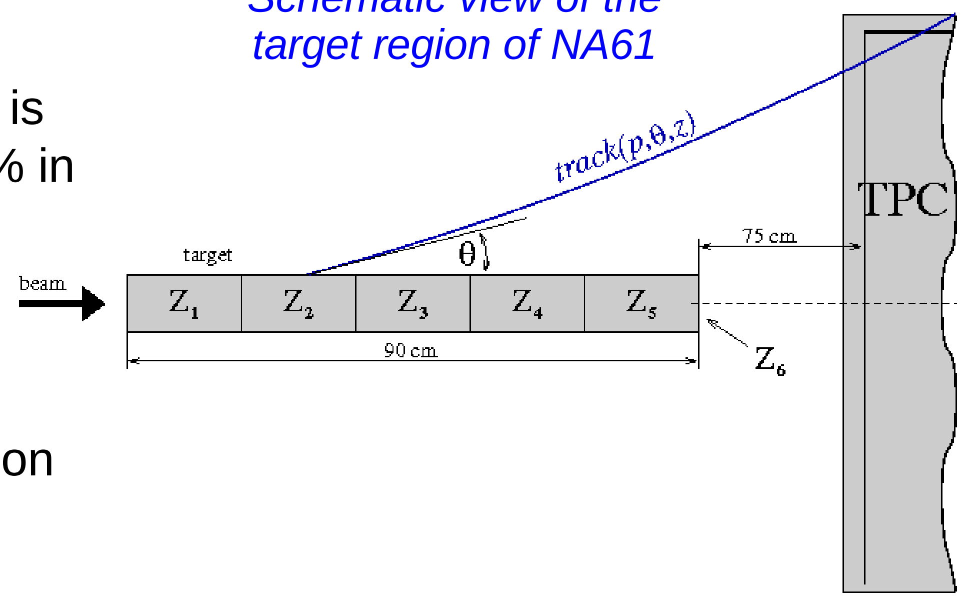
NA61 data for the T2K simulation

- Hadron multiplicities are parametrized **at the target surface** (no interaction vertex reconstruction)
- Model dependence of the ν flux prediction is reduced down to 10% as compared to 40% in the standard approach
- Analysis in bins of (p, θ, z)
- Target is subdivided into 6 z-bins
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Method is published: *NIM A701(2013)99*
  - $\pi^{\pm}$ analysis based on pilot data 2007

Schematic view of the target region of NA61



Summary of data collected by **NA61** for T2K

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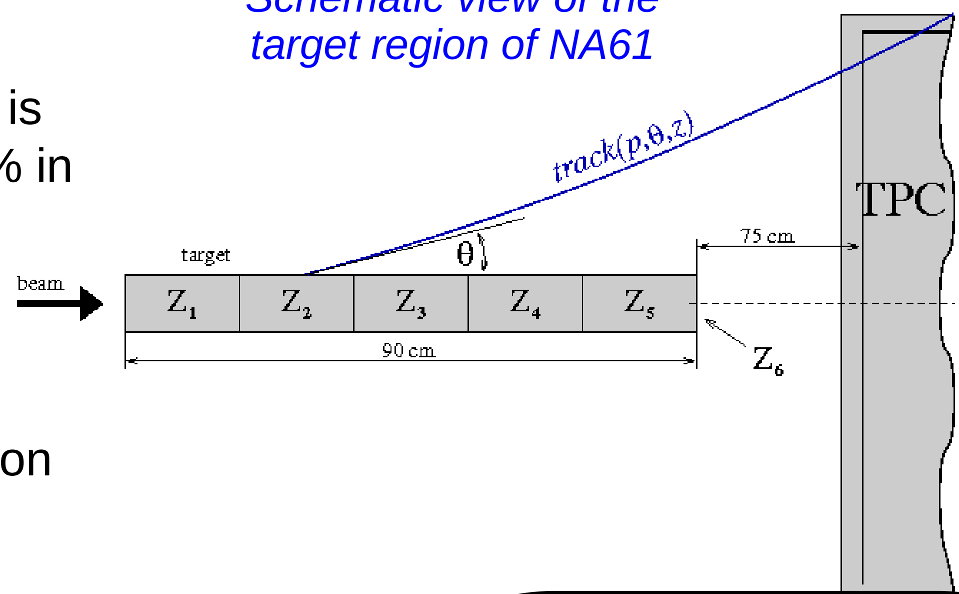

poster of A.Haesler
- **Spectra of π^+**
- **ν flux to be calculated**

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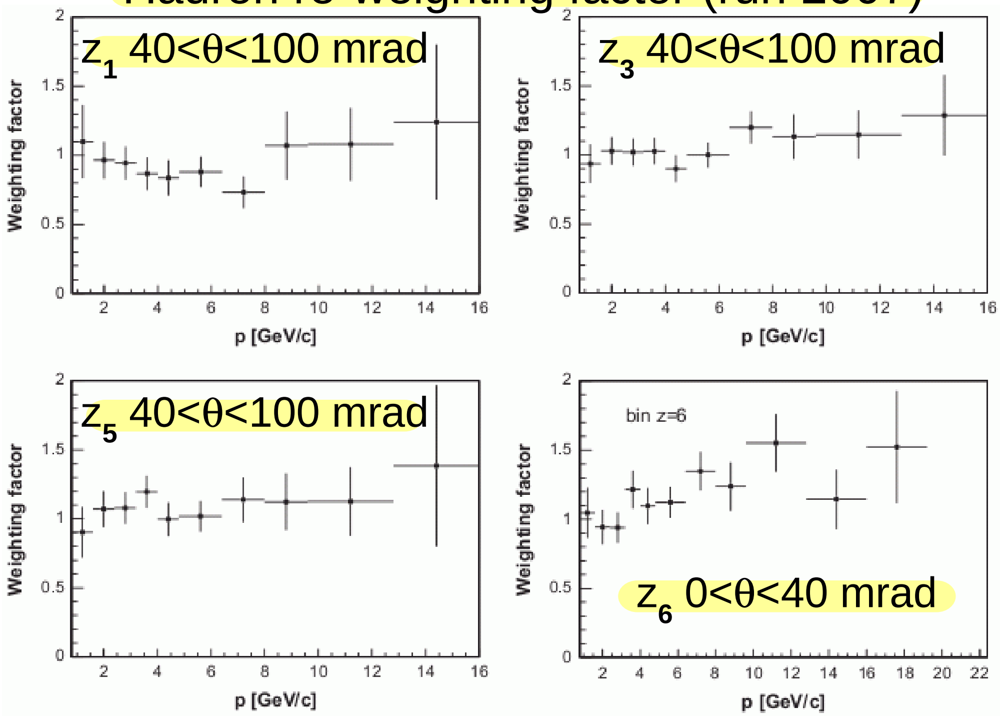
NA61 data for the T2K simulation

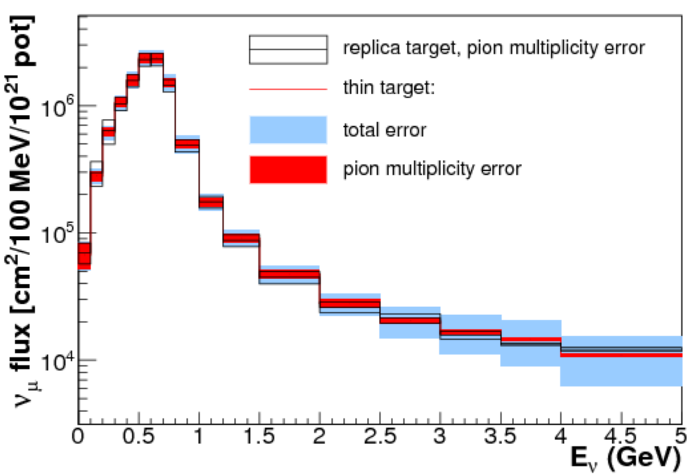
Hadron re-weighting factor (run 2007)

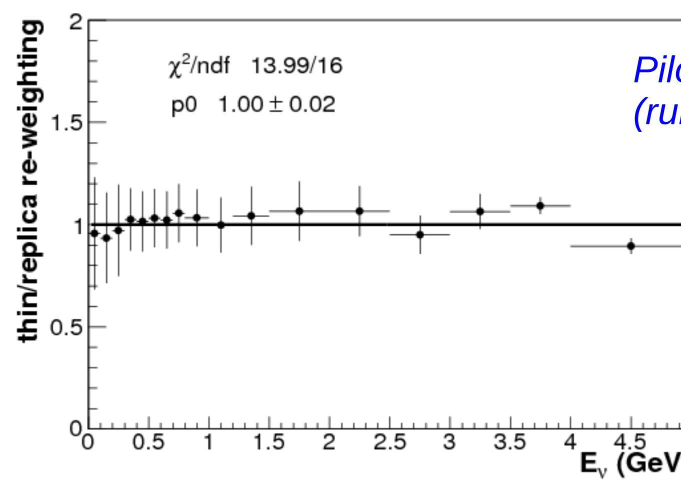


- Yields are measured at the target surface

$$w(p,\theta,z) = \frac{Data(p,\theta,z)}{FLUKA(p,\theta,z)}$$

- Good agreement between the traditional and the replica target methods ($\pi^{\pm}$ only)
- Statistical uncertainty is dominant
- Ultimate precision will come with the analysis of data 2009 and 2010



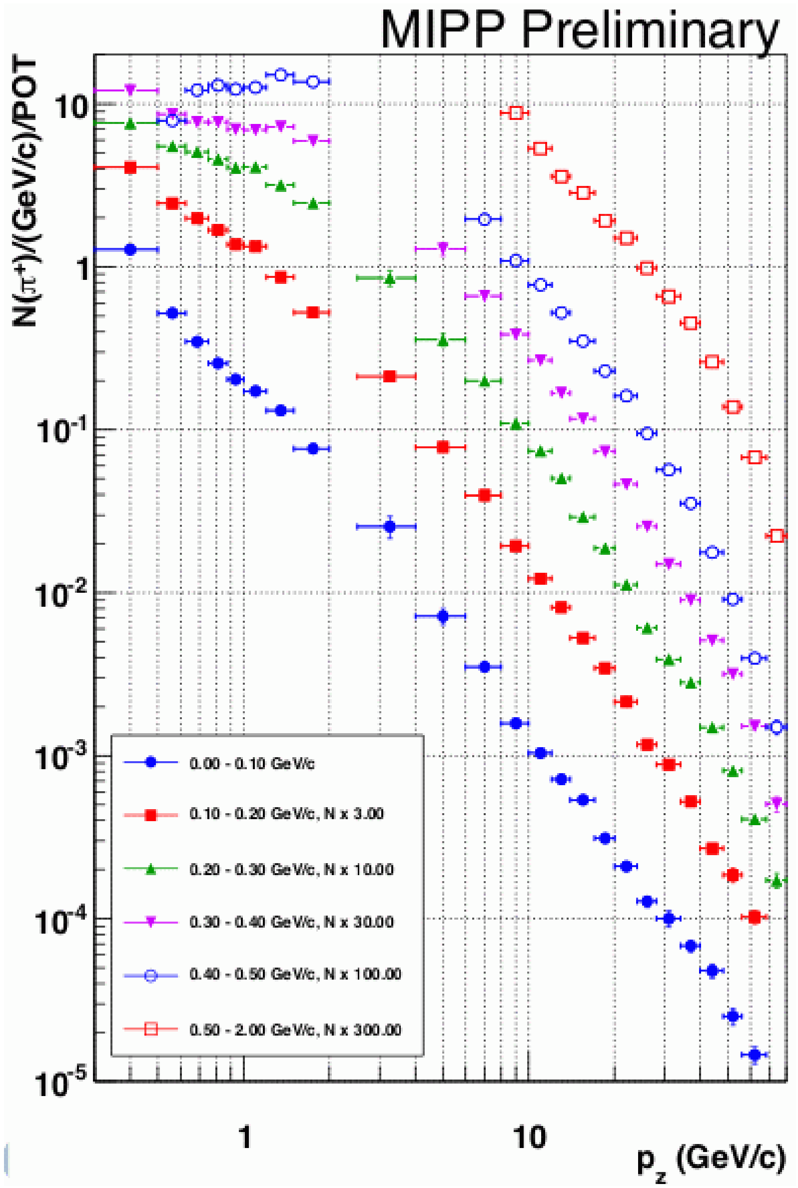


Pilot data of NA61 (run 2007)

(NA61) N.Abgrall et al., NIM A701(2003)99

MIPP data for the NuMI simulation

- 1.43×10^6 protons at 120 GeV on an actual NuMI target
- Measurement of the $\pi^{\pm}$ yield in ~125 bins of (p_z, p_T) across 2 orders of magnitude in momentum
- There is no binning in *z*
- For PID TPC (*dE/dx*) and RICH have been used
- Combined statistical and systematic errors are <10% in nearly all bins



(MIPP collaboration) J.Paley et al., arXiv:1404.5882, Apr 2014

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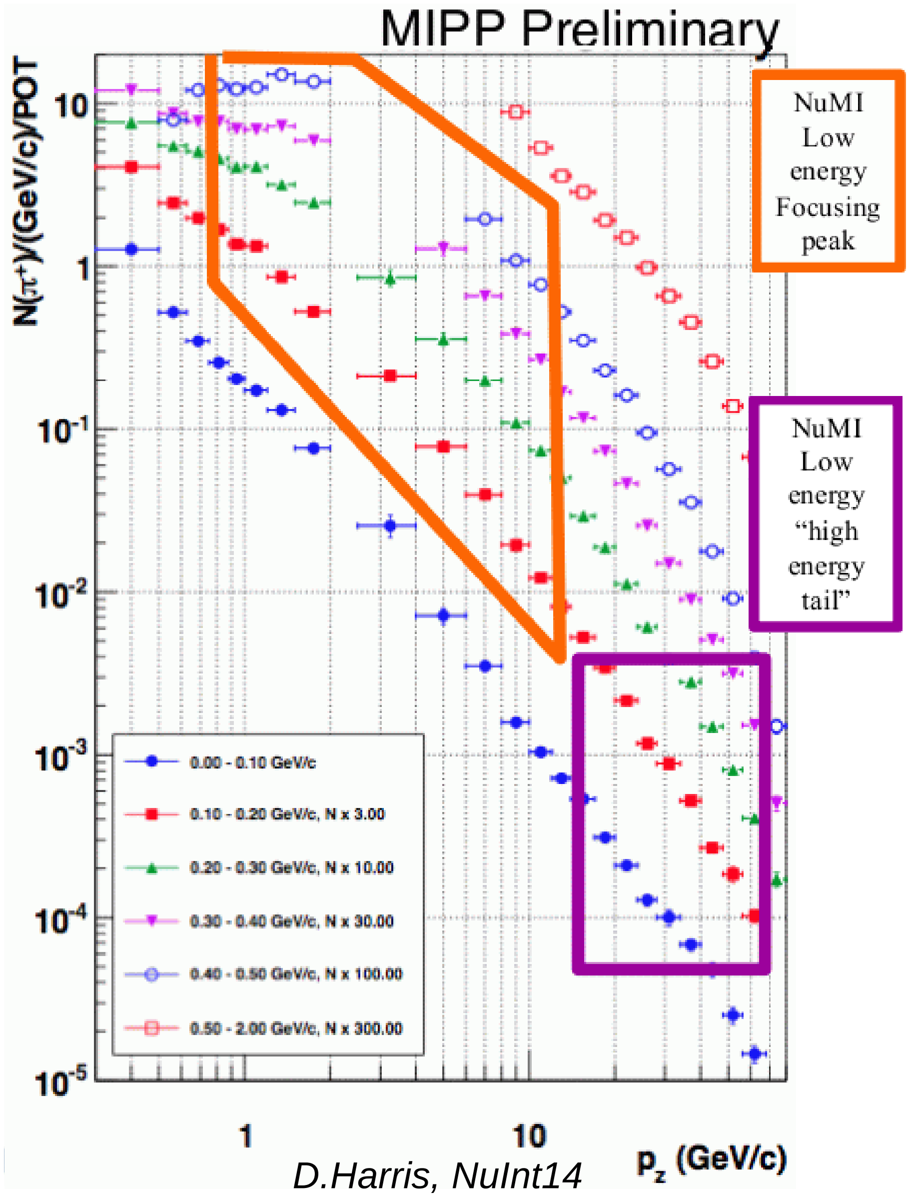
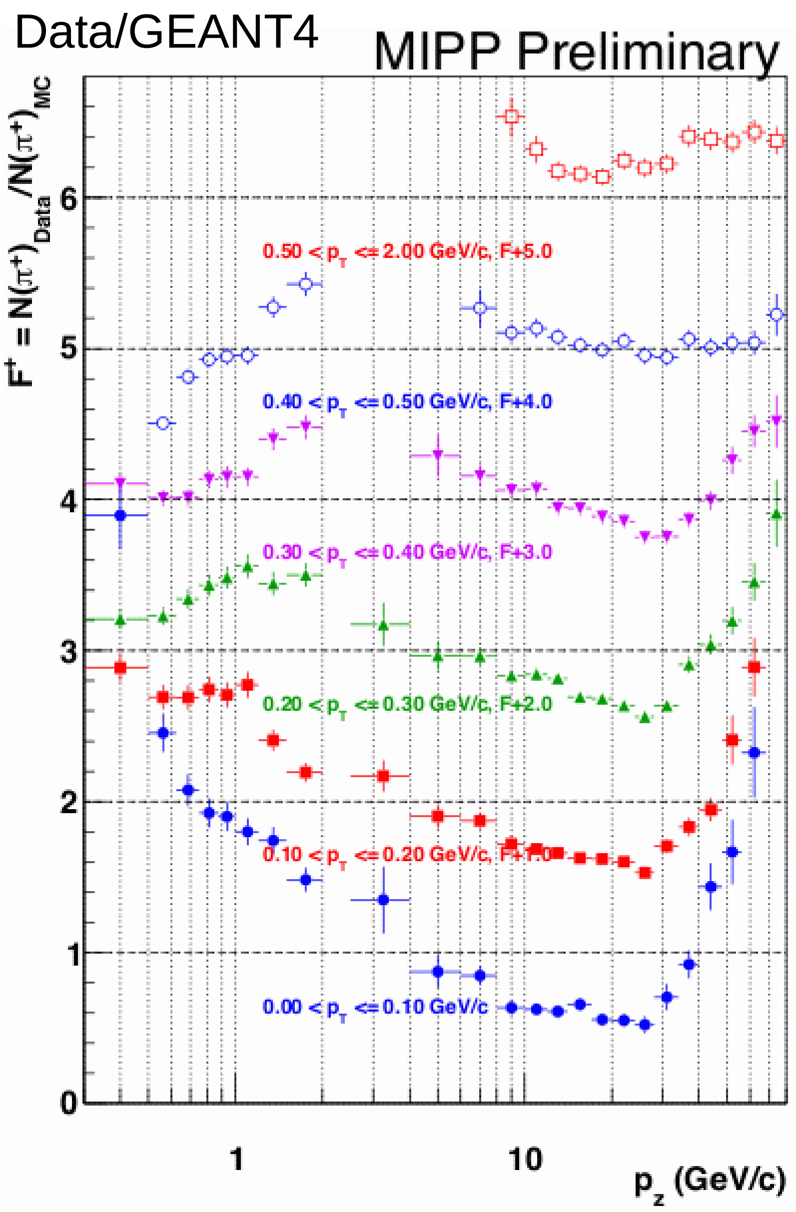


(MIPP collaboration) J.Paley et al., arXiv:1404.5882, Apr 2014

MIPP data for the NuMI simulation

- 1.43×10^6 protons at 120 GeV on an actual NuMI target
- Measurement of the $\pi^{\pm}$ yield in ~125 bins of (p_z, p_T) across 2 orders of magnitude in momentum
- There is no binning in *z*
- For PID TPC (*dE/dx*) and RICH have been used
- Combined statistical and systematic errors are <10% in nearly all bins
- Data imply that MCs tend to over-estimate pion yields at higher *p* and under-estimate at the focusing peak



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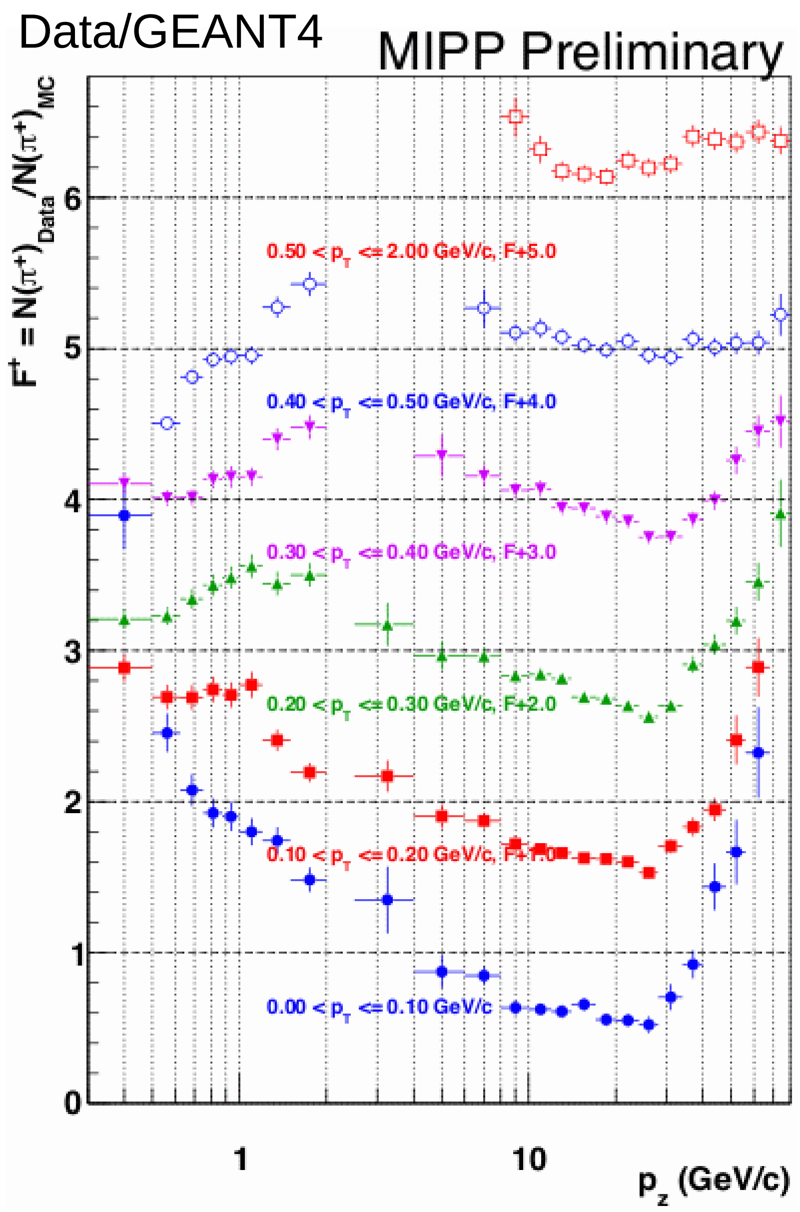
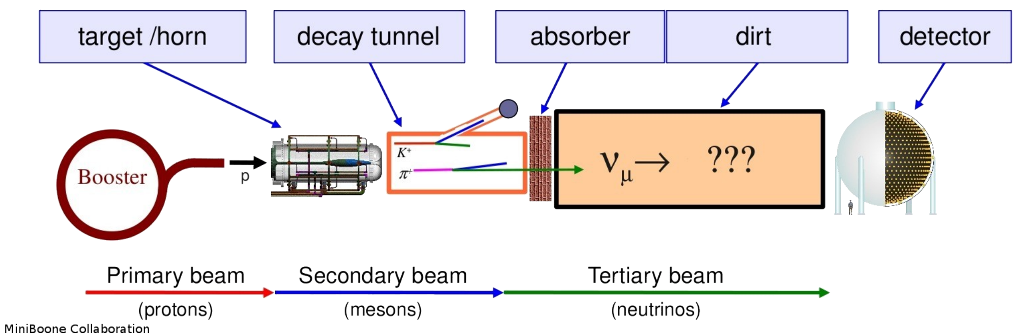


Conclusion

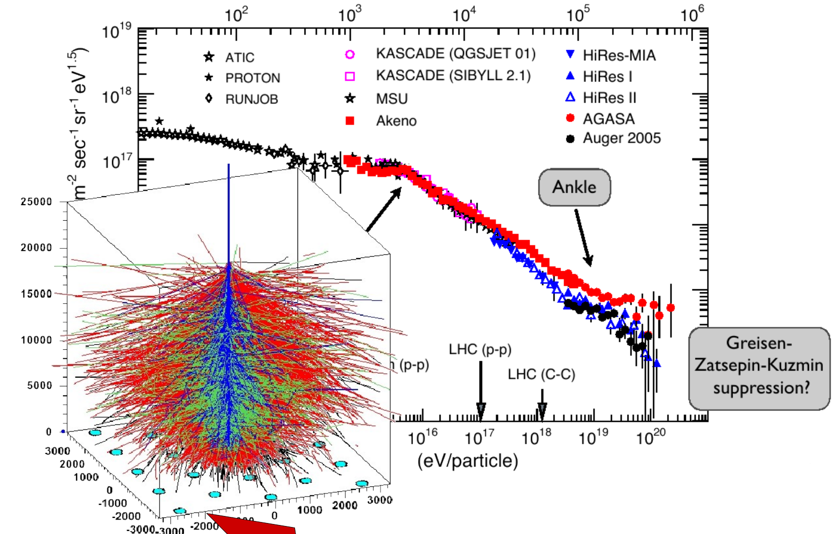
- Hadron production measurement is a cornerstone of the modern ν physics
- Traditional approach for the ν flux calculation: re-weighting the parent hadron multiplicity at the interaction vertex
  - NA61 data for T2K at 31 GeV,   also for NuMI at 120 GeV
  - NA49 data for NuMI at 158 GeV (scaled to 120 GeV)
  - Typical neutrino flux uncertainty is ~10%
- The actual target measurements:
  - NA61 data for T2K at 31 GeV
  - MIPP data for NuMI at 120 GeV
  - Reduction of model dependent uncertainties
- Precision measurements of hadron yields can be really difficult. Period from data taking to publication is typically $\gtrsim$ 4 years. *An ancillary experiment as much complicated as the main one!*
- Additional flux constraints using other methods could be also useful

backup

Conventional accelerator ν-beam



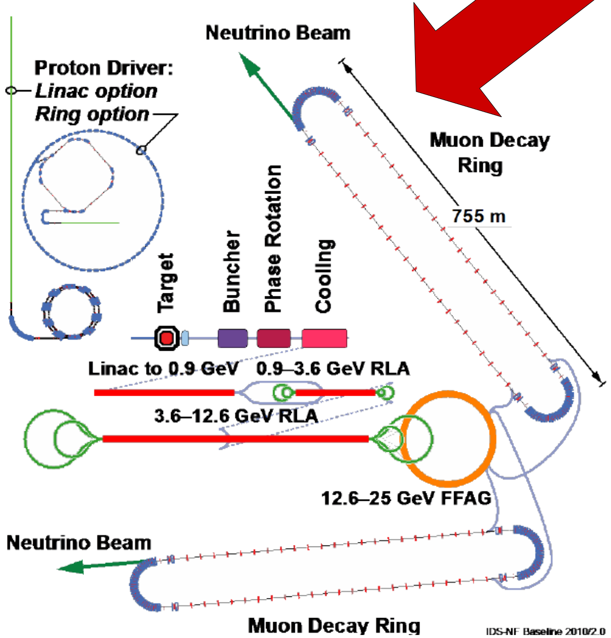
Atmospheric showers



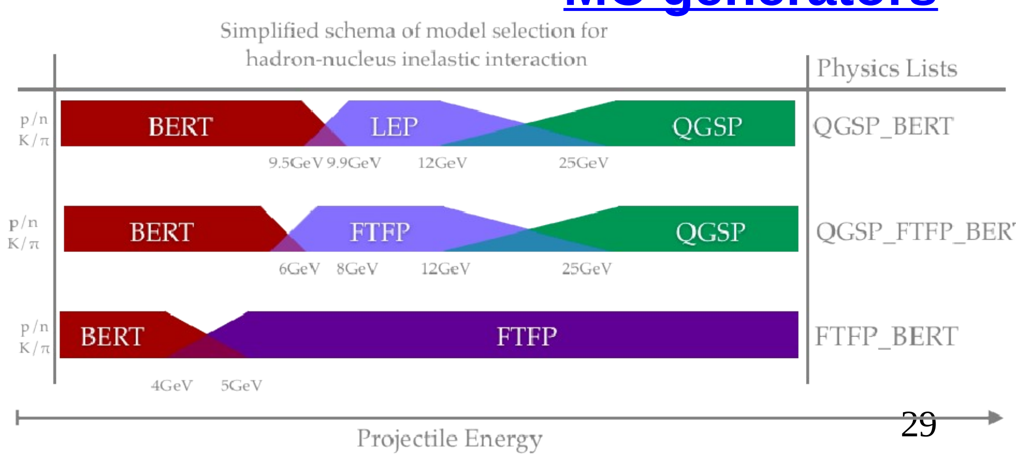
Hadroproduction measurement

$p(\pi) + A \rightarrow h + X$

Neutrino Factory



MC generators



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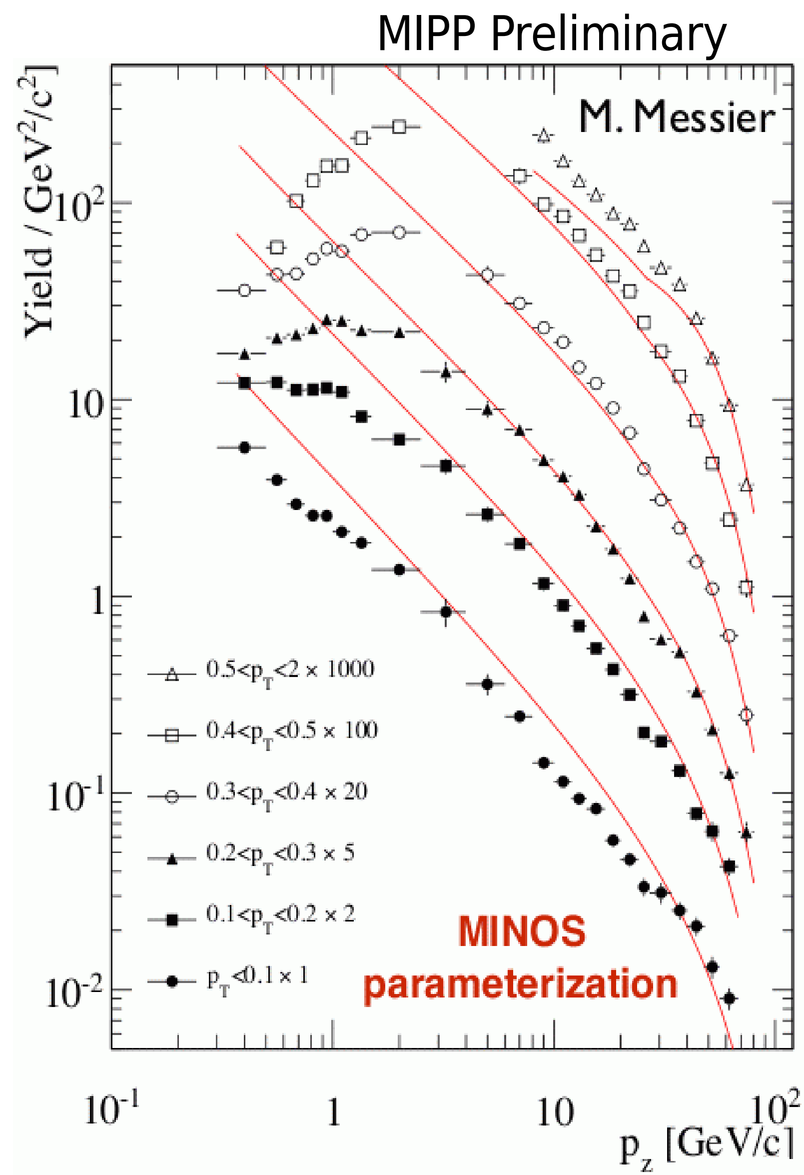
$$
\begin{aligned}
\frac{d^2N}{dp_Z dp_T} &= p_{\text{inc}}(A + Bp_T)e^{-Cp_T^{3/2}} \\
A &= a_1(1-x)^{a_2}(1+a_3x)x^{-a_4} \\
B &= b_1(1-x)^{b_2}(1+b_3x)x^{-b_4} \\
C &= -c_1/x^c + c_3 \quad \text{for} \quad x < 0.22 \\
C &= c_1/e^{(x+c_2)c_3+c_4x+c5} \quad \text{for} \quad x > 0.22
\end{aligned}
$$



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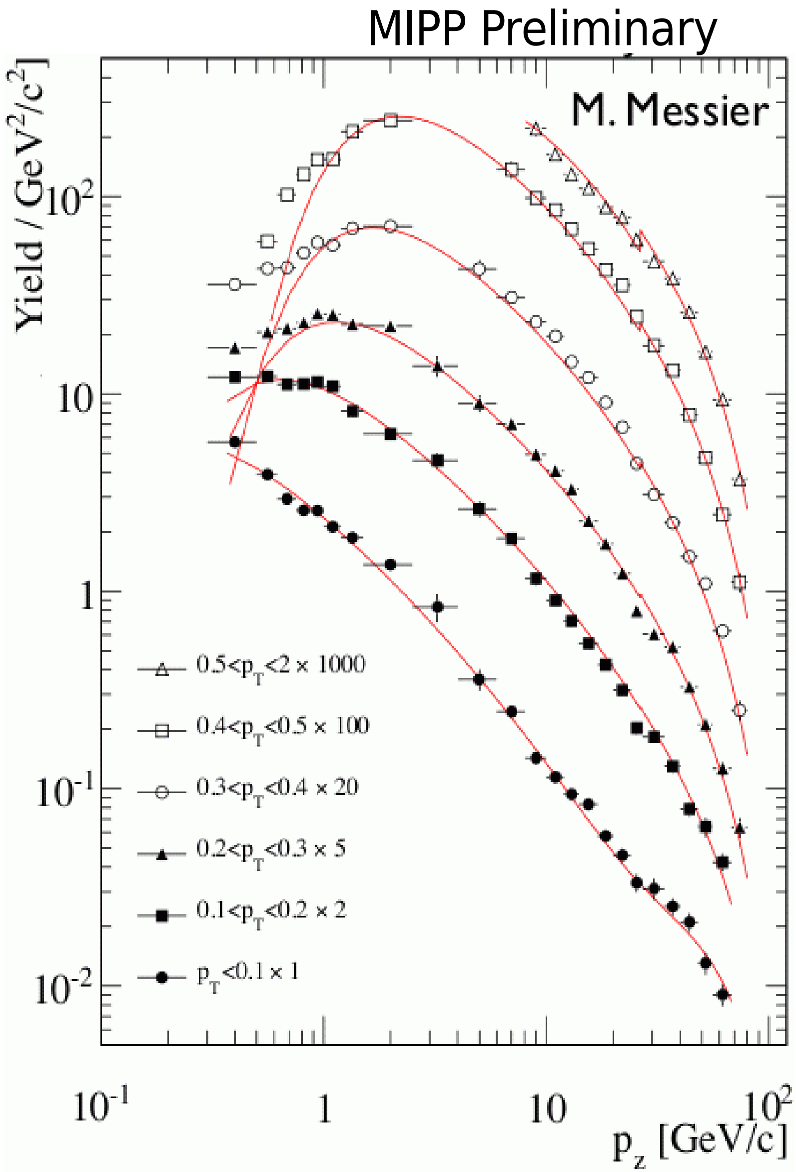

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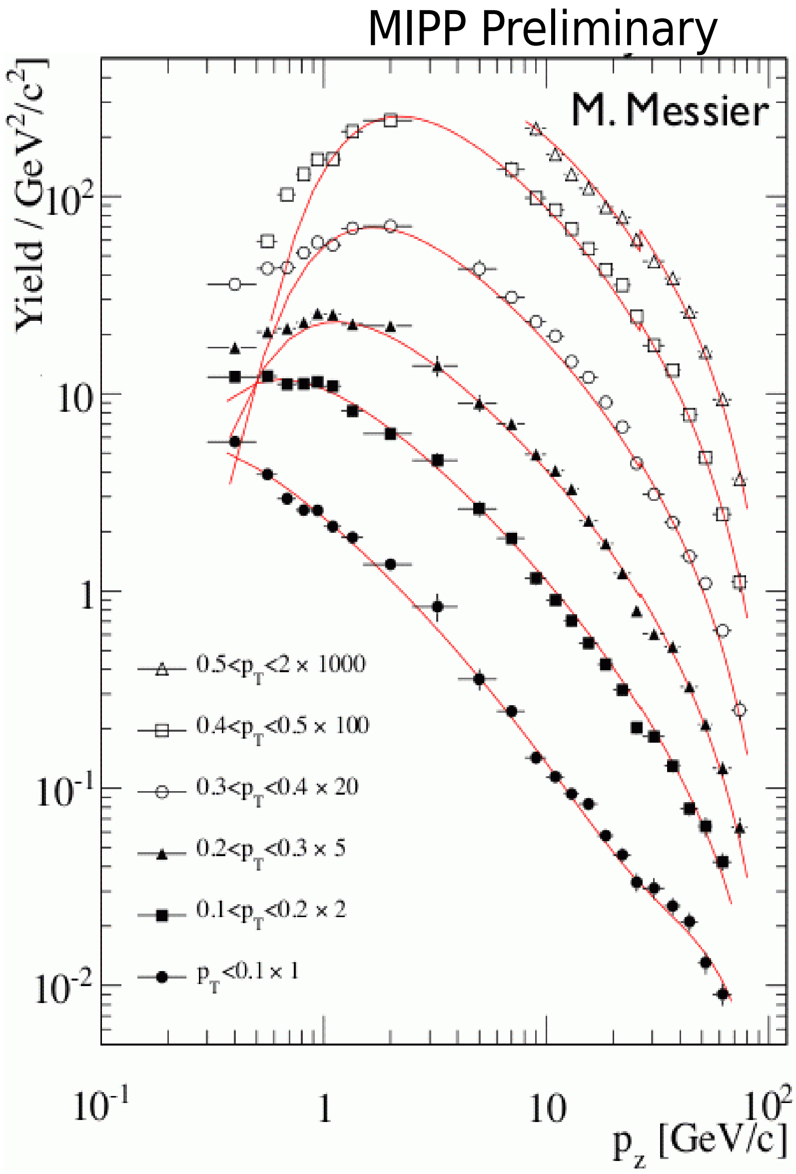
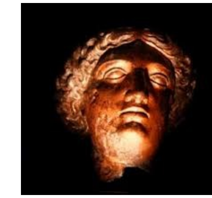
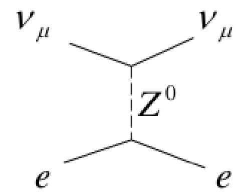


Direct measurement of ν flux with νe→νe



- Well known reaction

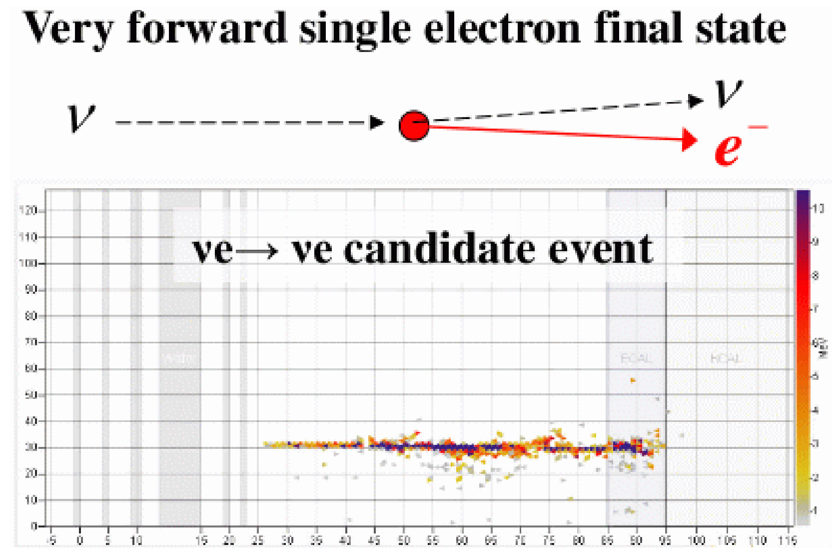
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

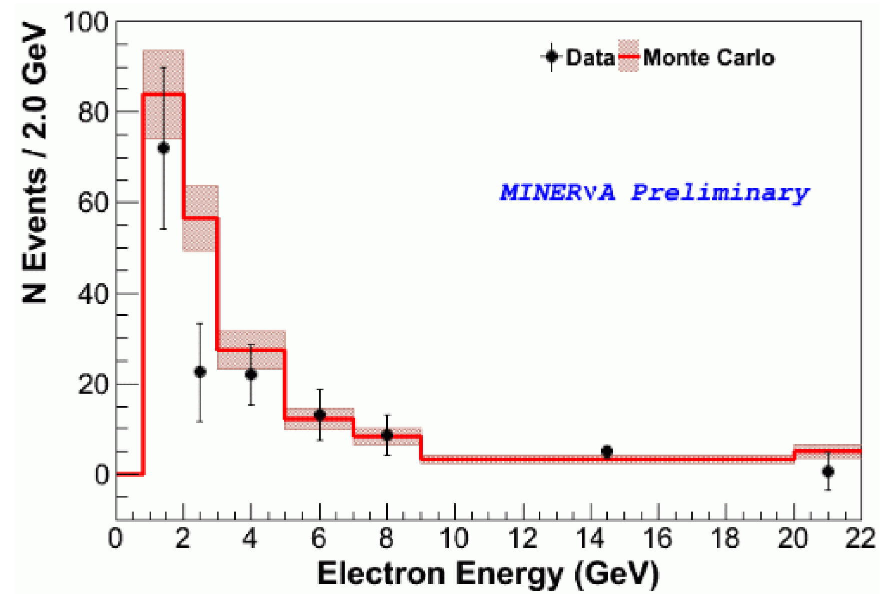


- Very small cross section (~1/2000 of ν-nucleon scattering)
- Very forward electron final state
- Background reactions

$$\nu_e + n \rightarrow e^- + p \qquad \nu_\mu A \rightarrow \nu_\mu A \pi^0$$
$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad \nu_\mu N \rightarrow \nu_\mu N \pi^0$$

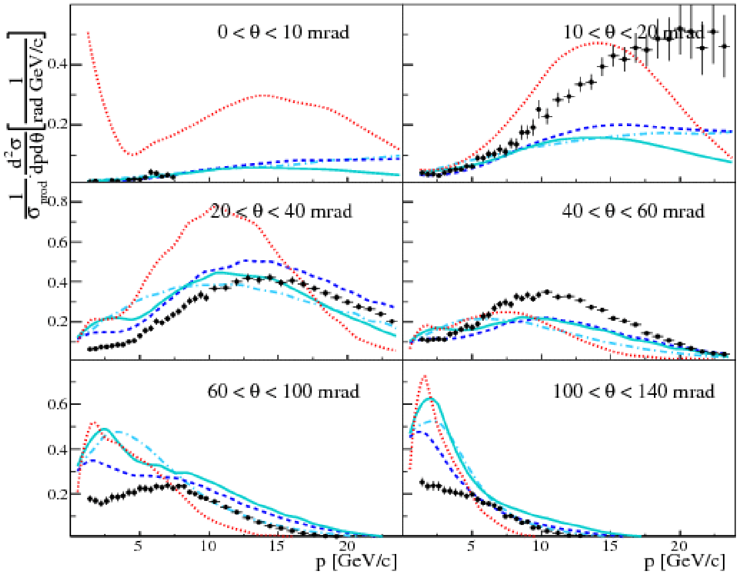
- νe events (LE) after all corrections:
  - **123.8±17.0(stat)±9.1(syst)**
- Prediction from simulation:
  - **147.5±22.9(flux)**
- In both cases precision is **~15%**
- Similar signal/background rate for ME as for LE
  - Expected stat. error ~2%
  - Syst. error 7% → 5%

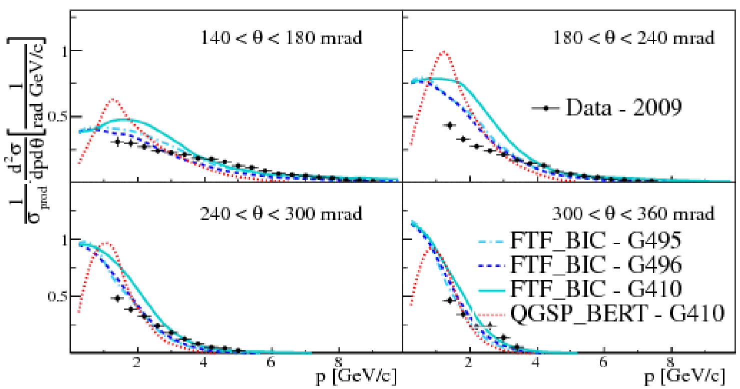




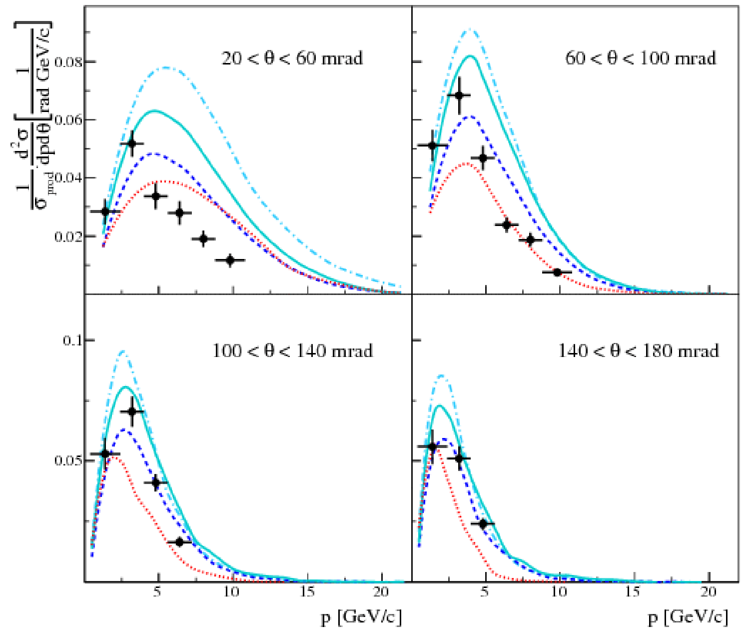
New NA61 measurements for T2K (pC@31GeV/c)

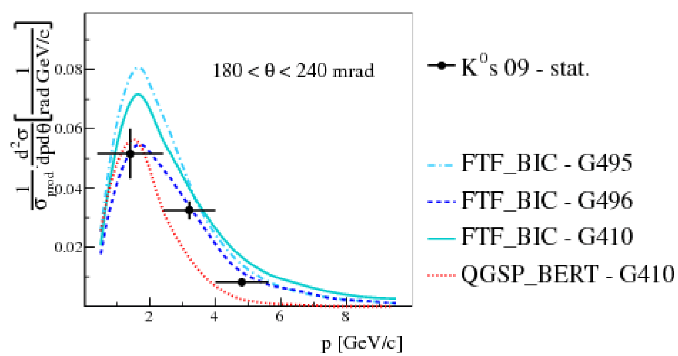
p + C → **p** + X





p + C → K^0_s + X



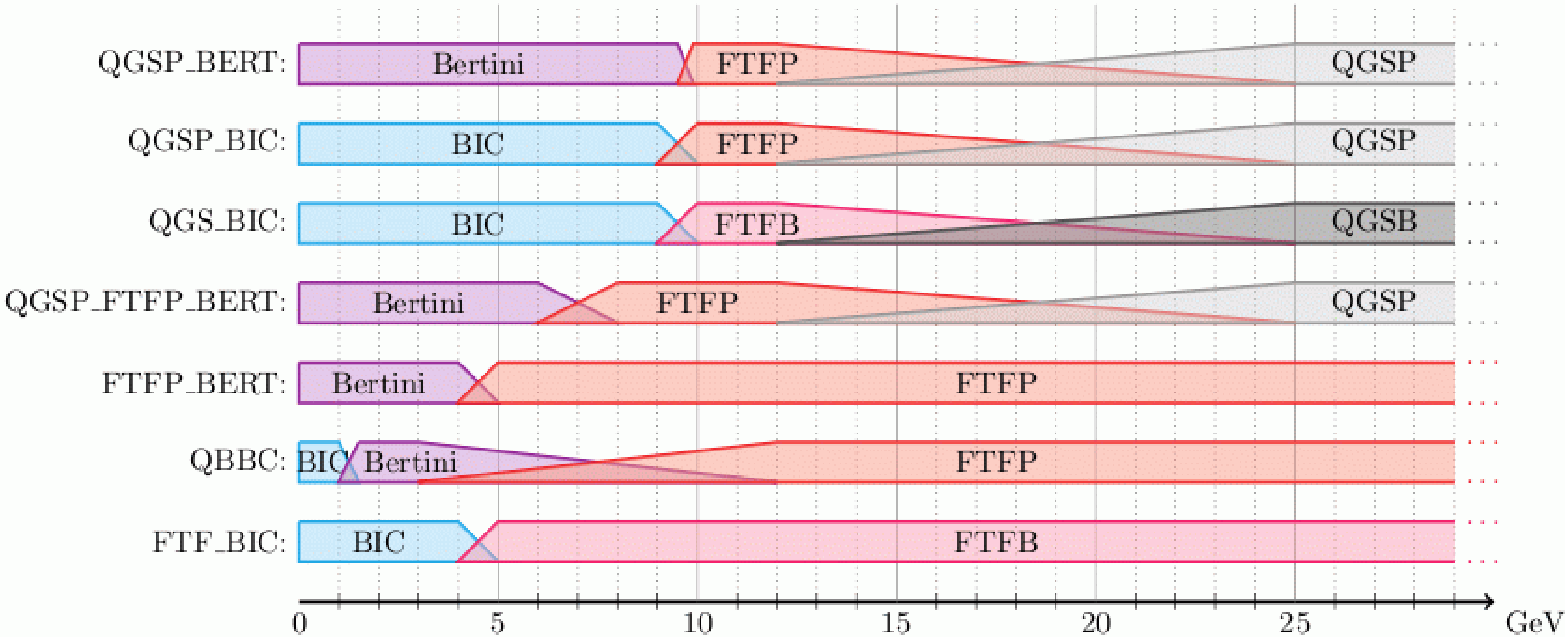


- New NA61 results based on data 2009. Precision improved by a factor 2-3 as compared to the pilot data 2007 (used so far by T2K)
- None of models can reasonably describe proton's spectra
- Recent versions of FTF_BIC describe K0S spectra reasonably

Update on physics lists

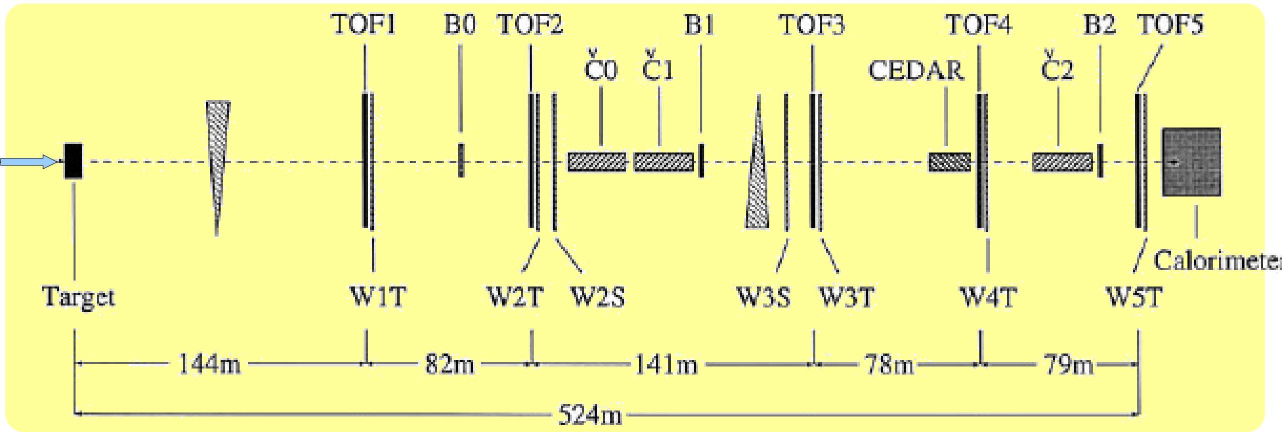
Composition of physics lists for proton interaction as a function of the energy

Now with **VMC 2.15** (**Geant4.10**)



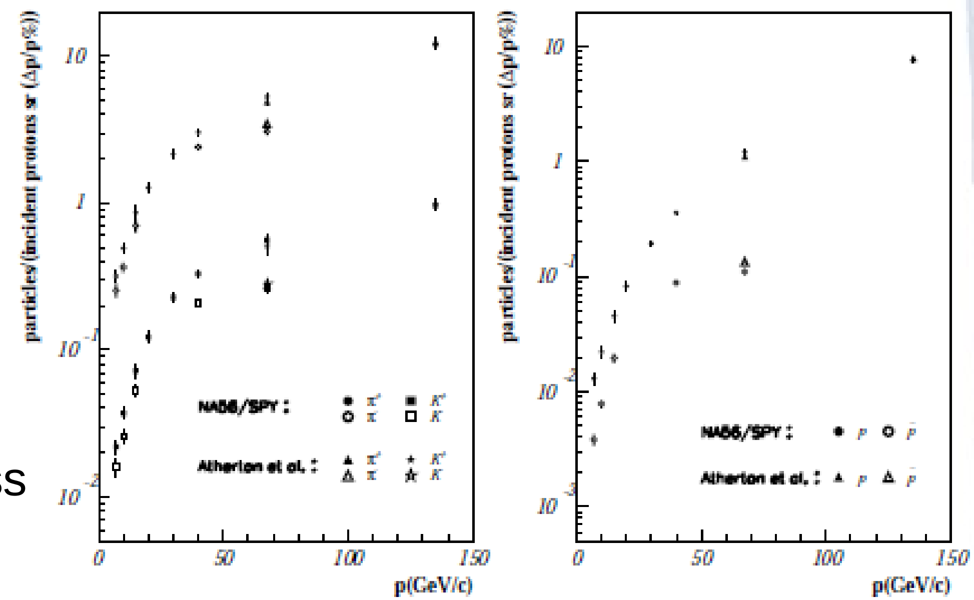
BIC: Binary Cascade Model
Bertini: Bertini Model
FTF: Fritiof Model
QGS: Quark Gluon String
~~**LHEP**: Low and High Energy Parametrized~~ REMOVED
-**P**: Precoumpound
-**B**: BIC

NA56/SPY, Secondary Particle Yields



- Goal: understanding and planing of ν oscillation experiments
- CERN-SPSLC/96-01
- H6 beamline of CERN SPS
- PID by TOF1-5, Cherenkov counters C0-C2 + CEDAR and Hadron Calorimeter

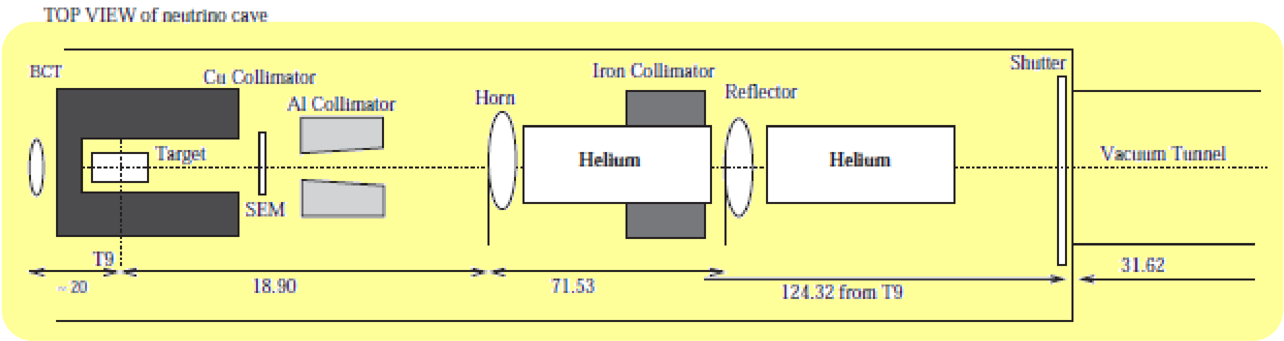
- 450 GeV/*c* protons interact with Be target
- Production angle up to 30 mrad
- Yields of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ have been studied
- Secondary momentum range 7-135 GeV/*c* ($0.02<x_F<0.3$) and $p_T<600$ MeV/*c*
- Experimental accuracy on yields 5-10%, for production ratios 3%
- Dependence of yields on the target thickness and shape have been studied
- Complementary to NA20 (Atherton et al.) measurements at 400 GeV/*c* and $0.15<x_F<0.75$



G.Ambrosini et al., Eur.Phys.J.C10(1999)605; Phys.Lett.B420(1998)225

SPY data in the NOMAD/WANF experiment

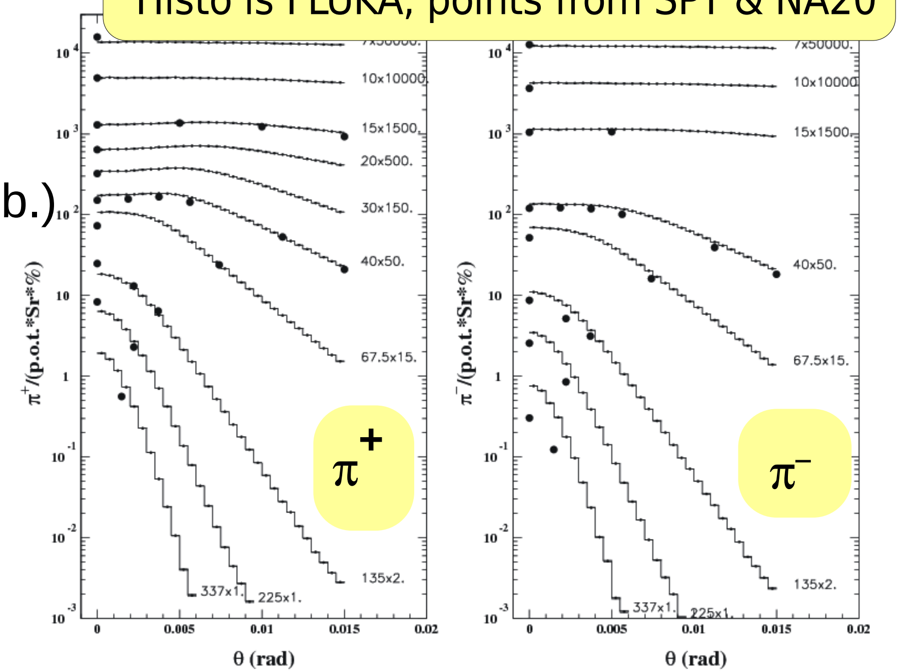
from SPS



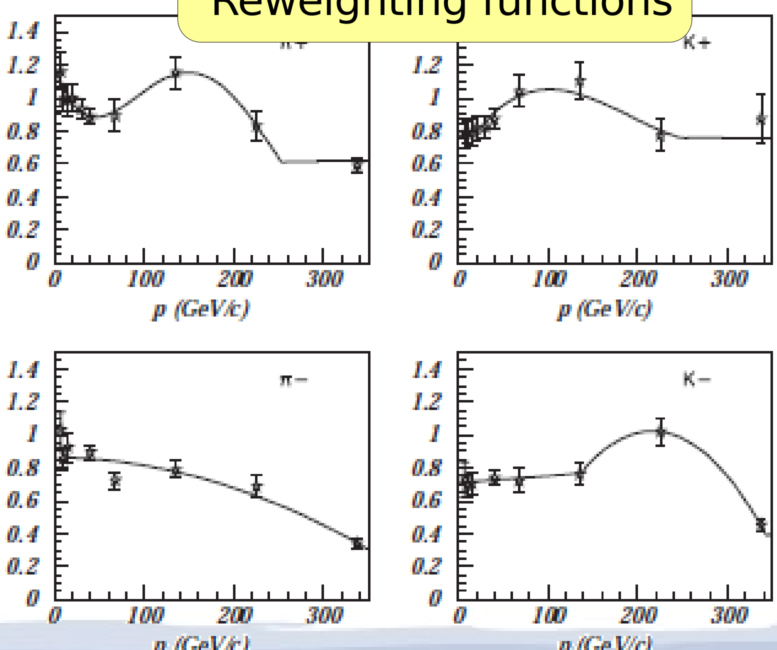
Towards CHORUS & NOMAD

- FLUKA 2000 was used to calculate rates
- Rates were modified to to account for cross-section measured by SPY and NA20
- Weight=Data/FLUKA for bin of p (and θ if posib.)

Histo is FLUKA, points from SPY & NA20



Reweighting functions



- Overall flux uncertainty 8% for ν_μ and ν_e, 10% for $\bar{\nu}_\mu$ and 12% for $\bar{\nu}_e$

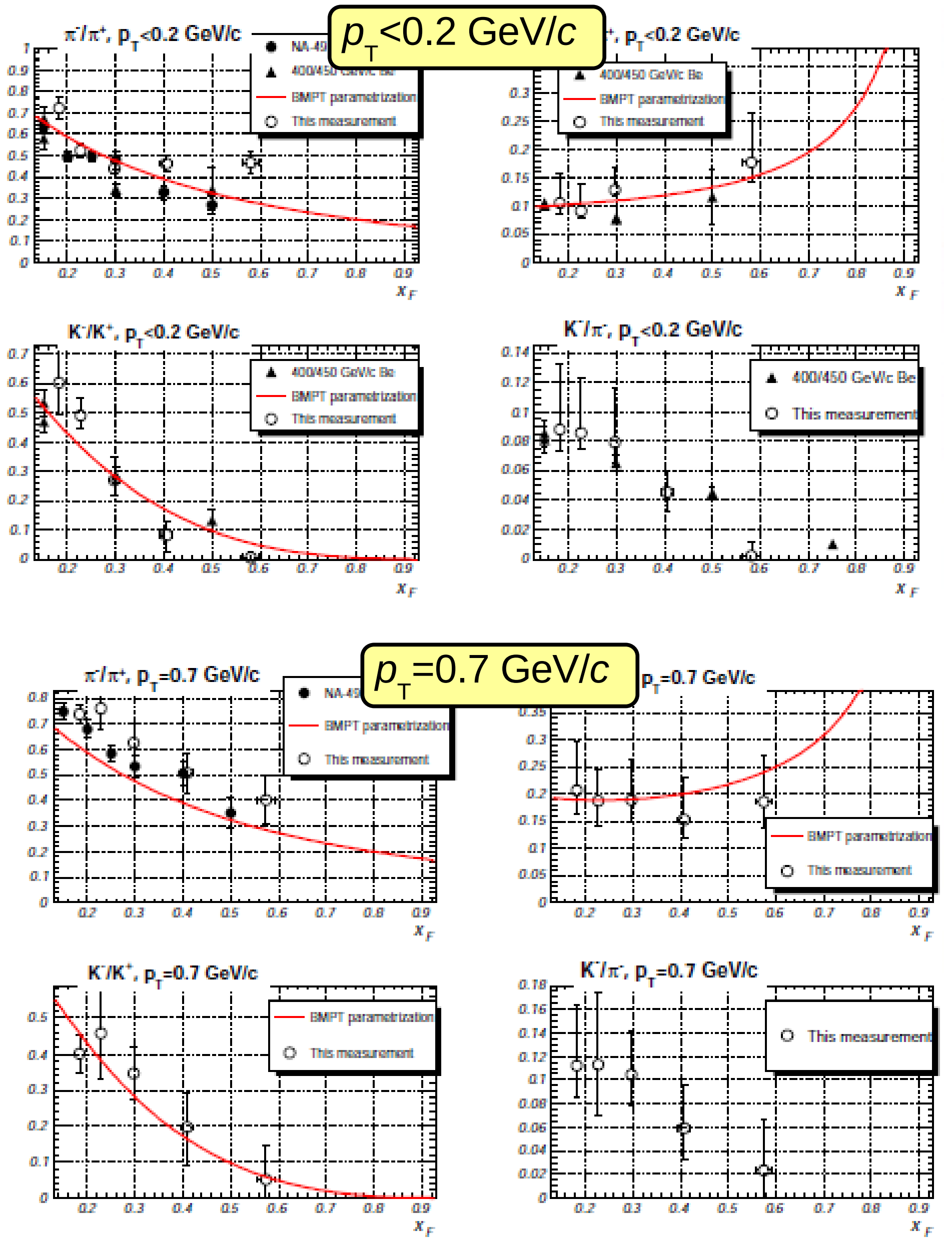
(NOMAD) P.Astier et al., NIM A515(2003)800
G.Collazuol et al., NIM A449(2000)609

Ratios of charged hadrons from MIPP

- Measurements for MINOS/ 120 GeV/*c*
  - Thin carbon target
  - NuMI replica target
- Preliminary results for ratios:

  π^-/π^+, K^+/π^+, K^-/K^+ and K^-/π^-

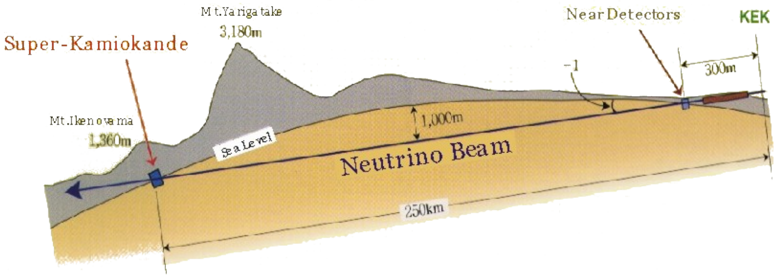
  H.Meyer, Nucl.Phys.B187(2009)197
- The only experiment nearby in phase space is NA49 (thin target, 158 GeV/*c* beam)
- Reasonable agreement of MIPP with NA49 and the MINOS spectrum fit has been found for p_{sec}<40 GeV/*c*
- BMPT parametrization (400 GeV/*c* protons on Be target) fits well the data



A.Lebedev, Ph.D. Thesis, Harvard U. (2007)

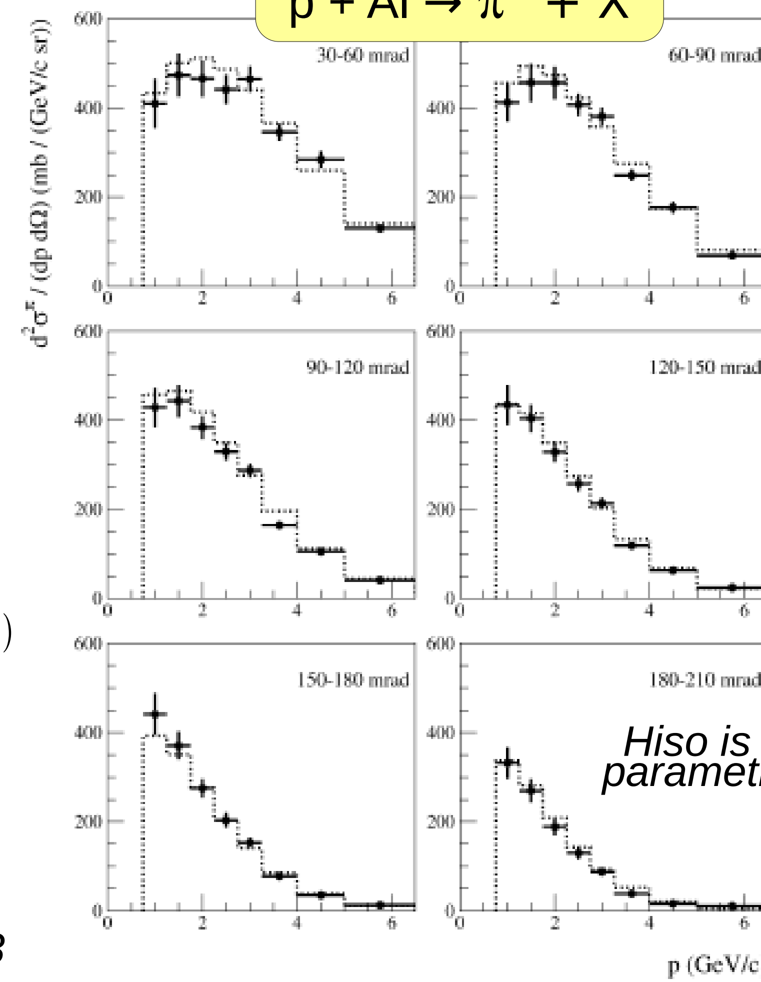
- New results: *Forward neutron production in MIPP*, *published in Phys.Rev.D83(2011)012002*

HARP data in the K2K experiment



- K2K measured ν_μ disappearance for θ_{23}, Δm_{23}^2
- ν_μ beam was produced by 12.9 GeV/c protons scattered off the Aluminum target

p + Al → π^+ + X



Hiso is the SW parametrization

- Measurement of $d^2\sigma^{\pi+}/dpd\Omega$
- Al target of 5% nuclear interaction length
- 0.21 M reconstructed secondary tracks in the forward spectrometer were used
- Overall scale error was ~6% and point-to-point error ~8.2%
- Sanford-Wang parametr. applied (χ^2/ndf=305/41)

$$\frac{d^2}{dp\,d\Omega}(p,\theta)=c_1 p^{c2}\left(1-\frac{p}{p_{beam}}\right)\exp\left[-c_3\frac{p^{c4}}{p_{beam}^{c5}}-c_6\theta(p-c_7 p_{beam}\cos^{c8}\theta)\right)$$

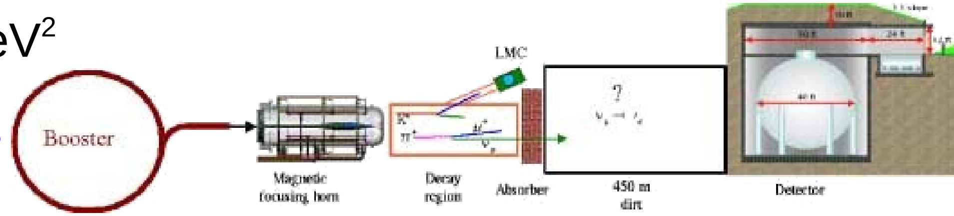
- Using HARP results the ν flux uncertainty to the far-to-near ratio in K2K was reduced by about factor 2: 5.1% → 2.9%

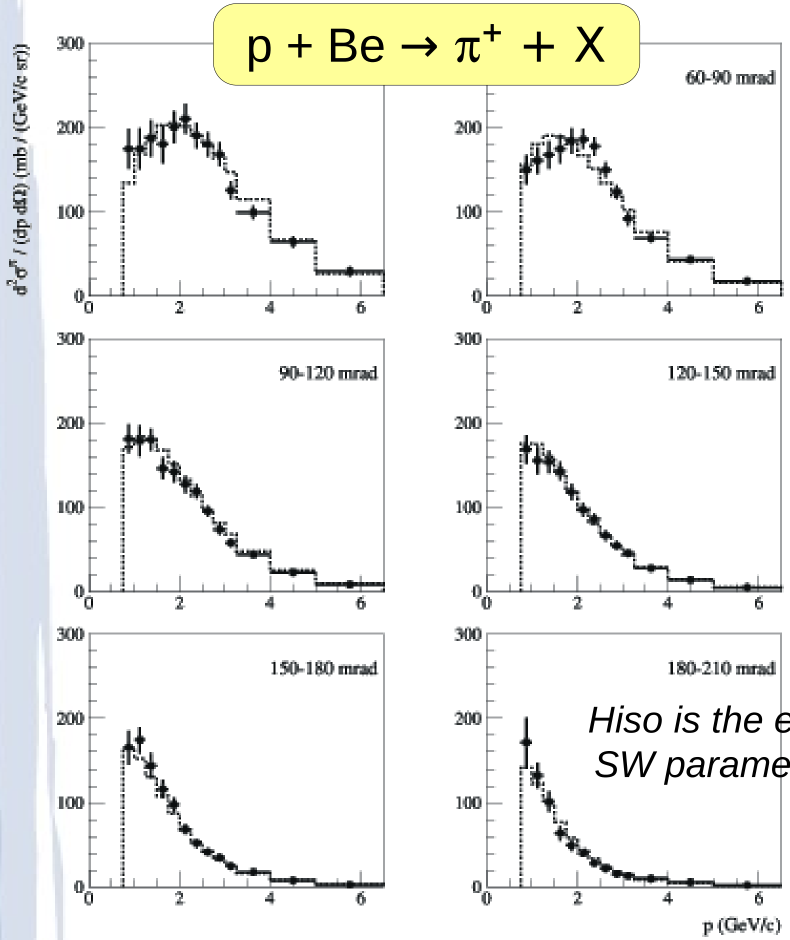
(K2K coll.) M.H.Ahn et al., Phys.Rev.D74(2006)072003

M.G. Catanesi et al., Nucl.Phys.B732(2006)1

HARP data in the MiniBooNE experiment

- MiniBooNE studied ν_e appearance at $\Delta m^2 \sim 1 eV^2$
- ν_μ beam was produced by 8.9 GeV/c protons incident on a Be target 71 cm long



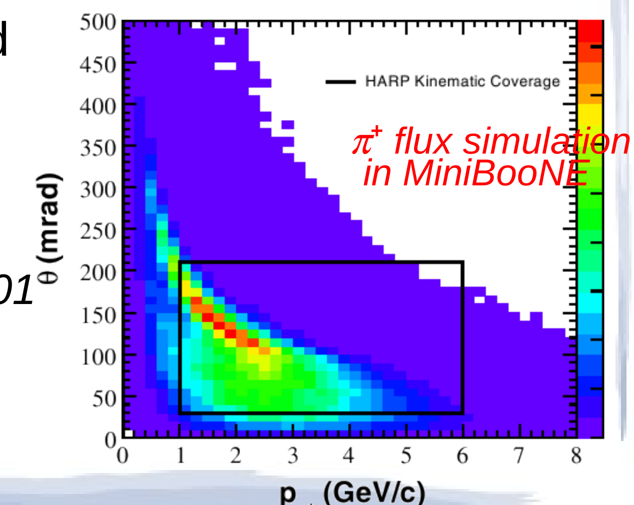


Hiso is the extended SW parametrization

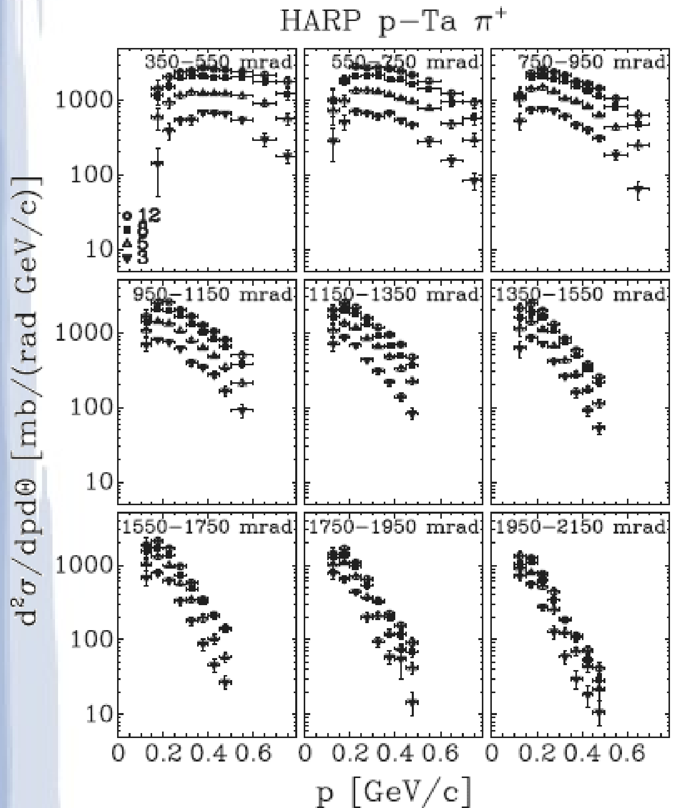
M.G. Catanesi et al., Eur.Phys.J.C52(2007)29

- Measurement of $d^2\sigma^{\pi+}/dpd\Omega$
- Be target of 5% nuclear interaction length
- 96 k reconstructed secondary tracks in the forward spectrometer were used
- Overall scale uncertainty was ~4.9% and point-to-point error ~9.8% (stat.+syst.)
- Sanford-Wang paramet. applied (χ^2/ndf=117/70)
- HARP results agree well with rescaled ones of BNL-E910 (6.4 & 12.3 GeV/c). Both were used to tune BNB beam MC

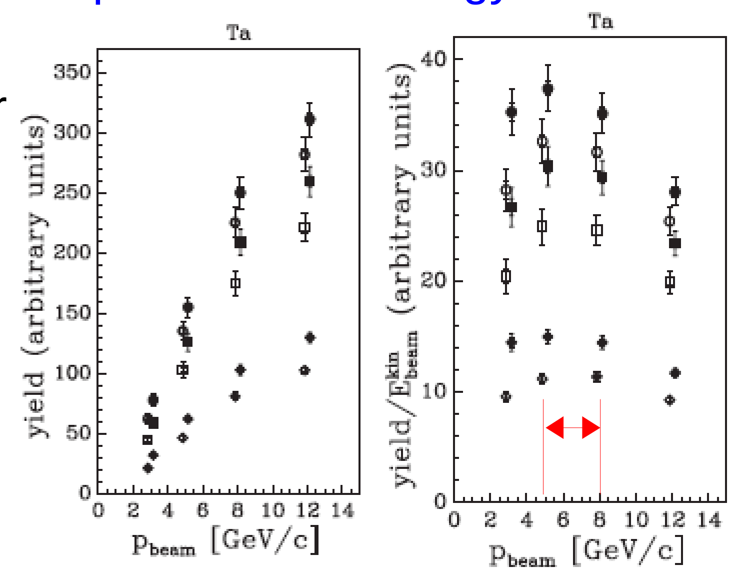
Phys.Rev.Lett.98(2007)231801
Phys.Rev.D79(2009)072002



HARP data & Neutrino Factory



- $\pi^{\pm}$ production in proton-(Be,C,Al,Cu,Sn,Ta,Pb) collision $3<p_{beam}<12.9$ GeV/*c*: *Phys.Rev.C77(2008)055207*
- Goal: determination of the optimal beam energy for the proton driver
- Simplified evaluation for the tantalum target
- Different symbols correspond to different θ integration range
- The optimum yield is between 5 and 8 GeV/*c*



J.Strait et al., Phys.Rev.Spec.13(2010)111001

- Double-differential cross sections were weighted by the acceptance of the front-end channel and integrated over the phase space of HARP
- Beam energy giving the largest muon yield at constant beam power is ~7 GeV
- No significant dependence on whether HARP or HARP-CDP input was used

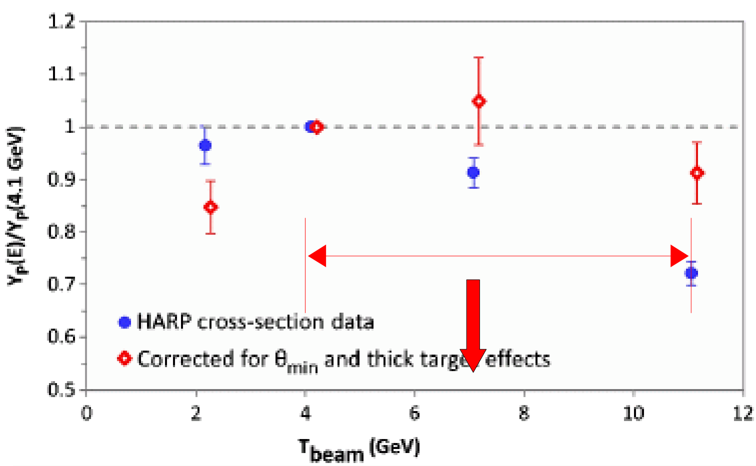
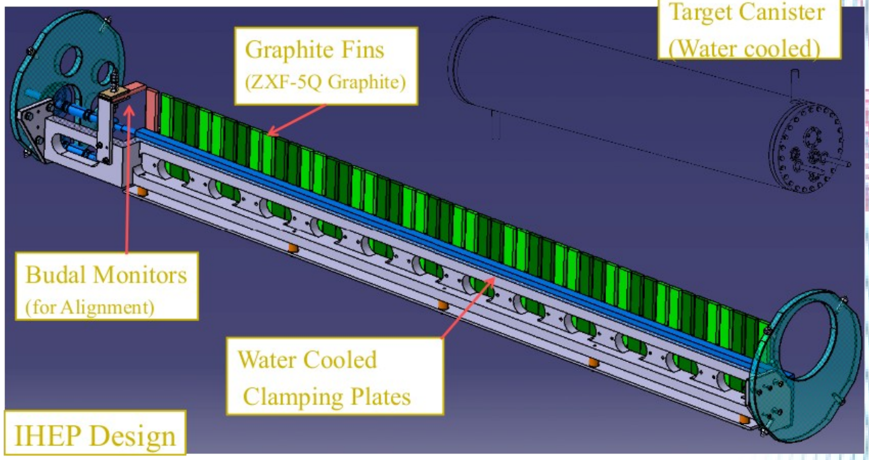


FIG. 9. Beam-power normalized muon yield at the end of the NF/MC front-end channel, relative to that at $T_{beam} = 4.1$ GeV.

Measurements for the NuMI target

- The goal is similar to the one for T2K (cross section + replica target)
- LBNE, MINOS(+), NOvA, MINERvA
- US group has been approved for limited membership at the beginning of 2012. Full members in 2014
- 22 physicists from 8 US institutions
- Pilot run in summer 2012
  - 120 GeV/c proton beam + C target
  - Non-standard magnet configuration
  - 3.5 millions triggers recorded
  - Calibration is in progress
- DOE proposal to be submitted
  - Upgrade of electronics (Pittsburgh)
  - Forward tracking (Colorado)
  - Request for 3-4 weeks of beam time (60, 90, 120 GeV/c, 3-4 targets)

Medium Energy Target for NOvA



NuMI target